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Non-symbolic magnitude processing is a strong correlate of symbolic math skills in children from Ghana and Côte d'Ivoire

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Title:

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Abstract

The ability to understand and compare non-symbolic (e.g., dot arrays) and symbolic (e.g., Arabic numerals) magnitudes is a critical foundation for learning math. A meta-analysis has revealed that symbolic magnitude processing is a stronger predictor of math performance than non-symbolic, but the evidence-base is restricted almost entirely to countries in the Minority World. It is unclear how the strength of the associations between symbolic and non-symbolic magnitude processing and math performance varies across contexts. An examination of cross-national similarities and differences in foundational numeracy skills is sorely needed. In the present study, we examine the predictive nature of symbolic and non-symbolic magnitude processing, in school-aged children from Ghana (n = 350) and Côte d'Ivoire (CIV; n = 342), two West African countries in the Majority World. Contrary to prior studies from countries in the Minority World, we found that non-symbolic magnitude processing was a significant and unique predictor of math performance in 5-to-13-year-olds from Ghana. The strong association remains significant when controlling for symbolic magnitude processing, literacy, executive functioning, and socio-emotional skills. A second pre-registered study with participants from Côte d'Ivoire revealed the same pattern of results. These associations diverged from those that have been found in the Minority World, and underscore the importance of taking a global perspective for understanding the cognitive precursors for math development. The data also highlight the potential to use the Numeracy Screener to measure children's understanding of numerical magnitude in classrooms around the world.

Keywords. Numerical magnitude processing, math achievement, sub-Saharan Africa

School entry numeracy skills are strong predictors of future academic success (Duncan et al., 2007; Romano et al., 2010). Despite growing rates of children accessing school around the world (e.g., World Bank, 2018), a large portion of children from the Majority World[1] who attend school fail to learn functional numeracy skills in the first three years of primary school (Sandefur, 2018). In sub-Saharan Africa specifically, fewer than one in five children attend any formal pre-primary education (McCoy et al., 2018) thus limiting children's exposure to formal learning environments before entering first grade. With global education goals shifting from access to school to access to high quality education (United Nations, 2015), improving early numeracy skills is critical to ensure improved learning outcomes. A deeper understanding of which foundational numeracy skills support math learning across diverse contexts, including settings where children have limited access to early learning opportunities, is essential for developing equitable and contextually relevant educational interventions.

Associations between Numerical Magnitude Processing and Math Performance

Learning abstract mathematical concepts, like mental arithmetic, stems from a basic understanding of numerical magnitude expressed using non-symbolic (e.g., collection of items) or symbolic representational formats (e.g., "five" or "5"). Symbolic representations of magnitude are inventions that require direct instruction to learn; learning their meaning is a gradual and challenging process (e.g., Sarnecka & Lee, 2009; Gobel et al., 2011). In contrast, the capacity to represent and mentally combine non-symbolic magnitudes is present at birth and shared across a variety of animal species. For example, human infants, preschool children who have not received formal training, and monkeys can perform approximate calculations using non-symbolic magnitudes (Barth et al., 2005; Brannon & Terrace, 1998; Brannon, 2002; Cantlon et al., 2016; de Hevia et al., 2020; Libertus & Brannon, 2009; Mccrink et al., 2017; Pica et al., 2004; Rugani et al., 2013; Xu & Spelke, 2000). Moreover, human adults from non-industrialized societies who have limited symbolic numerical systems show similar patterns of behavioral performance when discriminating between non-symbolic magnitudes relative to adults from industrialized societies (Piazza et al., 2013; Pica et al., 2004). The

[1] Terminology varies across international studies to refer to certain countries (e.g., non-Westernized Educated Industrialized Rich and Democratic (non-WEIRD), low- and middle- income countries (LMICs), and the Global South) varies. These terms can be problematic because they can perpetuate false hierarchies and dichotomies (Draper et al., 2022); however, they can serve a purpose to highlight inequalities and under-representation in developmental psychology research. We chose to adopt terminology recommended by Draper and colleagues to use Majority and Minority World to reflect collectively groups of countries where the majority and minority of the world's population live (Alam, 2008). The term "Majority World" was coined as an alternative to terms like "Third World", aiming to reframe the perspective by emphasizing what these countries have rather than what they lack (Alam, 2008). Majority World countries are primarily in Africa, parts of Asia, and Latin America. The Minority World countries represent a small fraction of the world's population and hold a disproportionate share of global wealth. They are typically located in North America, Western Europe, Australia/New Zealand.

ability to process symbolic and non-symbolic numerical magnitudes is often assessed using comparison tasks. In such tasks, participants are presented with either two arrays of dots (non-symbolic comparison task) or two Arabic numerals (symbolic comparison task) and asked to select the numerically larger magnitude. Accuracy and reaction time data are used as indices of the underlying precision of non-symbolic and symbolic magnitude representations.

Given the hierarchical nature of mathematics, a compelling theory is that non-symbolic magnitudes serve as ontogenetic and phylogenetic precursors for acquiring symbolic math skills (Dehaene, 1997; Pizza et al., 2010). According to this view, children learn the meaning of symbolic numbers by automatically mapping them onto pre-existing representations of approximate non-symbolic magnitudes. Support for this proposal comes from cross-sectional and longitudinal studies showing that children and adults who are more accurate at discriminating between non-symbolic magnitudes tend to score higher on standardized assessments of symbolic math ability (Chu et al., 2015; Feigenson et al., 2013; Halberda et al., 2008; Libertus et al., 2011). Although studies have failed to find a significant association between non-symbolic magnitude processing and symbolic math performance (e.g., Holloway & Ansari, 2009; Mundy & Gilmore, 2009; Sasanguie et al., 2013). Two recent meta-analyses have confirmed there is indeed a small but significant relation between non-symbolic magnitude processing and symbolic math skills (Chen & Li, 2014; Schneider et al., 2016). Some training studies have found that children who practice comparing or computing approximate magnitudes show significant gains in symbolic math skills (e.g., Hyde et al., 2014; Park et al., 2016), suggesting that non-symbolic magnitude representations play a foundational and potential causal role in acquiring symbolic math.

The extent to which non-symbolic magnitudes play a role in developing formal math skills remains contentious in the field (see Leibovich & Ansari, 2016; Szűcs & Myers, 2017; Wilkey & Ansari, 2019 for reviews). For example, researchers have argued that the observed association found between non-symbolic magnitude processing and math achievement may instead reflect domain general cognitive processes, such as inhibitory control (Leibovich & Ansari, 2016; Fuhs & McNeil, 2013; Gilmore et al., 2013; but see also Starr et al., 2017) and/or visual perceptual processing of dot stimuli (Gevers et al., 2016, but see also DeWind et al., 2015). Thus, tasks assessing non-symbolic magnitude skills may tap into several component skills, undermining the claim that they isolate core numerical skills and challenges the proposal that approximate magnitude processing plays a foundational role in symbolic math development. Further challenging this claim, several training studies have failed to find a causal link between approximate magnitude processes and symbolic math performance (e.g., Bugden et al., 2021; Ferres-Forga & Halberda, 2020; Kim et al., 2018; Szkudlarek et al., 2021, including a recent meta-analysis Qiu et al., 2021).

Alternately, studies that have examined the unique contributions of non-symbolic magnitude processing and symbolic number knowledge to math development have found that, while non-symbolic skills show a weak association with symbolic math, symbolic number knowledge is a stronger predictor prompting researchers to argue for a greater emphasis on developing early symbolic number skills. For example, Nosworthy et al., (2013) found that the association between non-symbolic magnitude processing, assessed using the Numeracy Screener (www.numeracyscreener.org) – paper and pencil non-symbolic and symbolic comparison tasks, and arithmetic performance was no longer significant once they accounted for other variables, such as working memory, reading, and symbolic magnitude skills. Hawes and colleagues (2019) additionally found that symbolic comparison performance assessed using the Numeracy Screener (Nosworthy et al., 2013) in Kindergarten predicted teacher assigned math grades in first grade. In contrast, non-symbolic comparison performance was not a significant predictor of math grades (Hawes et al., 2019). These studies suggest that symbolic magnitude processing skills are a stronger predictor of math abilities (relative to non-symbolic magnitude processing). This pattern of results have been corroborated in longitudinal studies showing that symbolic comparison performance at school entry are a stronger predictor of future math achievement (Xenidou-Dervou et al., 2017) and future symbolic numerical skills (Lyons et al., 2018; Matejko & Ansari, 2016) even when controlling for non-symbolic magnitude processes. Compared to the research findings on non-symbolic magnitude processing, there is stronger and consistent evidence to support the proposition that symbolic magnitude skills play a more important role in developing math abilities. However, almost all of the studies exploring whether symbolic and non-symbolic magnitude processes are foundational for developing formal math skills come from the Minority World. The associations between non-symbolic and symbolic magnitude representations and symbolic math development across diverse countries and contexts (i.e., diverse learning environments and situational settings; exposure to numbers in daily life) has been largely overlooked in the literature. It remains an open question the extent to which the link between non-symbolic magnitude representations and symbolic mathematics are universal across different cultures.

Symbolic and Non-symbolic Comparison Skills across Cultures

Researchers have explored whether the unique associations between non-symbolic, symbolic magnitude processing, and arithmetic skills varied in different countries. Rodic et al., (2015) collected samples in China, UK, Russia, and Kyrgyzstan. They found that symbolic comparison accounted for significant unique variance in arithmetic skills in all countries. Non-symbolic comparison performance was not a unique correlate of arithmetic performance. Similarly, Tavakoli (2016) found that symbolic comparison performance measured using the Numeracy Screener in a large sample of second grade boys from Iran was a unique correlate of speeded and non-speeded calculation skills when controlling for non-symbolic comparison performance, working memory, processing speed, and long-term memory. Consistent with the findings from Canadian samples using the Numeracy Screener (Hawes et al., 2019; Nosworthy et al., 2013), non-symbolic comparison performance was not a significant correlate of arithmetic skills. These studies suggest that symbolic magnitude skills are an important foundation for acquiring symbolic arithmetic across different cultures.

Contextual Variation in Numerical and Math Development

The majority of cross-cultural studies exploring the associations between numerical magnitude skills and math performance are carried out in high or upper-middle income countries (except for Kyrgyzstan, which is characterized by the UN has a lower-middle income country; United Nations, 2019). Research exploring the development of symbolic and non-symbolic magnitudes skills, as well their associations with math achievement are predominantly studied in the Minority World. Cross-cultural research is essential for testing whether the mechanisms underlying math development generalize beyond findings that stem from the Minority World (Henrich et al., 2010; Nielsen et al., 2017). There are several lines of evidence to suggest that socio-cultural and educational contexts may influence numerical and mathematical development. One line of evidence comes from international comparisons that have consistently found that Asian students outperform students from Europe and the United States on general numerical and mathematical tests (e.g., Imbo & LeFevre, 2009; Siegler & Mu, 2008). Beyond cross-cultural comparisons, the home math environment, which includes parents engaging in math-specific activities and dialogue with their children, as well as their attitudes and beliefs about math, is associated with children's math achievement (e.g., Daucourt et al., 2021), suggesting that children's home experiences influence math development.

The transition to formal schooling also has a significant impact on the development of arithmetic and symbolic magnitude skills independent of age-related maturational changes (Vandecruys et al., 2025). And while the ability to discriminate between non-symbolic magnitudes has been considered universal across species and cultures (Dehaene, 1997; Pica et al., 2004); Rodic et al. (2015) found that children from Russia and China outperformed children from the UK and Krgyzstan on the non-symbolic comparison task. Similarly, Piazza et al. (2013) found that education level, more than age, predicted non-symbolic comparison performance in an indigene group. Taken together, these findings provide support that culture and education shapes both non-symbolic and symbolic math development.

The broad aim of our study is to explore the associations between symbolic and non-symbolic numerical magnitude processing and general math abilities in children from two Majority World countries in West Africa, where cultural and educational contexts differ than previously studied countries, and where research is sorely lacking (Nielsen et al., 2017).

Education in sub-Saharan Africa

Compared to other Majority World regions, sub-Saharan Africa has the largest proportion of children living in poverty and that are stunted, with some of the poorest learning outcomes globally (Angrist et al., 2021). Although, global progress has been made to improve early childhood educational access, ~~though~~ concerns about poor quality persist (Yoshikawa et al., 2018). Since 2000, the percentage of primary school children unenrolled in sub-Saharan Africa has declined from 40% to 22% (UIS Data Center – UNESCO Institute for Statistics). Yet, many children and adolescents within the classroom are not achieving basic numeracy and literacy skills (Sandefur, 2018). One way to improve learning outcomes is to supply teachers with feasible evidence informed screening tools for classroom so they can monitor their students' progress. Teachers who can identify gaps in their students' learning could adapt their lesson plans, and allocate already limited resources to students who need them most (Linzarini et al., 2022). The first step to achieving this goal is to examine the underlying mechanisms that support math development across diverse socio-cultural contexts.

The Ghanaian and Ivorian Contexts

We addressed this gap in the literature by conducting two studies exploring the foundational numeracy skills important for math learning in children from two Majority World countries: Ghana (Study 1) and Côte d'Ivoire (CIV; Study 2). While our study samples come from two neighboring countries in West Africa, Ghana and CIV provide an interesting point of comparison within the West African context. In 2004, the government in Ghana adopted the National Early Childhood Care and Development Policy, which highlighted access to quality early education as central to improving ECD and learning as well as to reducing inequalities in learning outcomes. In 2007, 2 years of pre-primary education—called *kindergarten 1* (KG1; the equivalent to pre-K in the United States) and *kindergarten*

2 (KG2; the equivalent to kindergarten in the United States), respectively—were added to the universal basic education system that had previously begun in the first grade of primary school. Ghana has among the highest enrollment in preprimary school across the continent, with gross enrollment at 116% and primary school gross enrollment rates at 97% (World Bank, 2024). Despite high enrollment rates among school-aged children in Ghana, learning outcomes remain slow. For instance, 70% of second grade students and 80% of fourth grade students are unable to read simple words or perform basic arithmetic problems (World Bank, 2018). Our sample in Ghana is drawn from the Greater Accra region and is urban and peri-urban, and is the most densely populated and fastest growing region in the country. It holds significant diversity in terms of economic, linguistic, and ethnic groups (Ghana Statistical Service, 2022).

On the other hand, CIV is a francophone lower-middle-income country with a similarly sized population as of 31 million (World Bank, 2024). CIV does not have a universal preprimary school system and has very low rates of preprimary school enrollment at 10.7% gross enrollment but high rates of primary school gross enrollment at 102% (World Bank, 2025). Côte d'Ivoire ranks among the bottom 30 countries globally in learning outcomes (Angrist et al., 2021), with large inequalities between urban and rural regions (PASEC, 2020). Our sample in Côte d'Ivoire is drawn from rural cocoa-farming communities in the Aboisso and Bouaflé regions of Côte d'Ivoire. Thirty eight percent of children reported working in cocoa production to support their family's economic well-being. Reports were higher among children living in rural areas (Lichand & Wolf, 2025). Higher child employment is associated with higher school drop-out rates and lower test scores (Lichand & Wolf, 2025; Sadhu et al., 2020). Among primary school children in CIV, 19% of students in Aboisso met or exceeded minimum proficiency level in reading and 18% did so in math. In Bouaflé, only 9.4% achieved minimum level in reading and 7% in numeracy. Together, these two samples from Ghana and CIV offer a valuable opportunity to examine the associations among non-symbolic and symbolic magnitude processing skills and math readiness in children from two neighboring yet culturally distinct, West African countries.

The Current Study

Study one was an exploratory investigation to examine whether individual differences in non-symbolic and symbolic magnitude processing was associated with symbolic math performance in primary school children from Ghana. We administered the Numeracy Screener (www.numeracyscreener.org), which is an easy to use, free paper and pencil assessment tool designed to measure non-symbolic and symbolic numerical magnitude knowledge across different educational contexts. In the symbolic condition, children compared pairs of Arabic numerals (e.g., “3 and 5”) and indicated which is larger, while in the non-symbolic condition, they compared pairs of dot arrays. The Numeracy Screener has been shown to be a reliable and valid predictor of math achievement in Minority World contexts (Hawes et al., 2019; Nosworthy et al., 2013). Therefore, we examined whether performance on the Numeracy Screener was associated with performance on the Early Grade Math Assessment (EGMA; RTI, 2009a), a standardized tool developed to assess foundational math readiness skills in early primary school children, particularly in low- and middle- income country contexts. Drawing on prior findings using the Numeracy Screener (e.g., Hawes et al., 2019; Nosworthy et al., 2013), and the strong emphasis placed on symbolic magnitude knowledge for developing math skills, our exploratory hypothesis is that symbolic comparison performance would explain unique variance in math readiness scores when controlling for non-symbolic comparison performance. After completing Study 1, we conducted a second pre-registered study in Côte d’Ivoire to examine whether the pattern we observed in Ghana could be replicated in a neighboring, but different regional and educational context.

Study 1 in Ghana

Methods

Participants

369 children from Ghana participated in the study and were in either the first or second grade of primary school. Children were removed from the final data analyses they obtained a score of 0 on either the symbolic or non-symbolic conditions of the numeracy screener (n = 19). None of the children reached ceiling performance. The final sample included 350 children (male, n = 189, female, n = 159, unknown = 2). Accurate age data was difficult to obtain, because families do not have birth certificates or track birthdays in the same way as is typical in Western contexts. Of the 350 children, we were able to collect age information using school records for 274 participants. Children were between 5-13 years of age (M_{age} = 7.68 years, SD = 1.33). Children were sampled at the end of the school year and therefore had between 3-4 years of formal school.

Materials

Math skills

Early numeracy and arithmetic skills were assessed using The Early Grade Math Assessment (EGMA) (RTI International, 2009a). The EGMA is an oral assessment of early numeracy and arithmetic operations. The Number Identification, Quantity Discrimination, Addition, Subtraction, Word Problems, and Missing Number subtests were administered (Cronbach’s α = .87). Across all subtests, if children spent more than five seconds on one item, they were asked to move onto the next trial. Administration of a subtest ended when they made four successive errors. A score was calculated by computing a mean percent correct for each subtest. Participants' math performance was calculated by computing a mean percent correct across all six math subtests.

Number Identification. The Number Identification subtest consists of 20 items that required children to identify increasingly larger single, double, and triple-digit numerals. Children were presented a card with all the numerals on it and asked to point to each number and tell the experimenter what it is. Children were given one minute to complete as many items as they could.

Quantity Discrimination. Children were presented with pairs of either single, double-, or triple-digit numerals and asked to indicate which number was bigger. They were first given two practice trials with feedback followed by 10 test trials. Five trials were shown on a stimulus card at a time. Children were given unlimited time to complete the test.

Addition and Subtraction. Children are shown a stimulus card with 10 addition problems and asked to say the answer for each problem. If they did not know the answer, they were asked to skip it and move onto the next problem. When the first 10 problems were completed, they were given the next stimulus card with 10 more problems. The addition problems increased in difficulty whereby the second half of the problems included double digit numerals. Children were given one minute to complete as many problems as they could. Participants were given paper, pencil, and counters if needed. The subtraction subtest was similar to the addition, but instead children completed subtraction problems.

Word Problems. Children were asked to solve verbally presented math story problems (e.g., There are 5 seats on the bus, there are 2 children on each seat. How many children are on the bus altogether?). Children were given two practice trials with feedback followed by six test problems. Children were given unlimited time to calculate the solution, as well as paper, pencil, and counters in case they were needed.

Missing Number. Children are presented three numerals with a space indicating a number is missing from the sequence (e.g., 1, 2 __, 4 "Here are some numbers one, two and four"), and were asked what number completes the missing part of the sequence (e.g., "What number goes here"). Single, double, and triple-digit numeral sequences were administered in increasingly more difficult order. A total of 10 test trials were administered. Five trials were presented on a stimulus card at one time. Children were given unlimited time to complete the test.

Literacy Skills

Literacy skills were measured across five domains of literacy and pre-literacy skills were measured primarily with the Early Grade Reading Assessment (EGRA; RTI International, 2009b). Children completed an oral vocabulary task where they were presented with pictures of objects and asked to name them (8 items). To assess listening comprehension, the experimenter read a short story aloud and asked the participants three questions related to its content. Letter-sound identification was assessed by asking children to produce the sounds of visually presented letters. Children also completed a nonword decoding task where they presented with made-up words in English and asked to read as many as they can. Across all subtests from the EGRA, for the exception of listening comprehension, children were given 60 seconds to answer as many as items as they could correctly. A measure of phonological awareness from the International Development and Early Learning Assessment (IDELA; Pisani, Dowd, & Borisova, 2018) was also included. In this task, children were presented with a target word and asked to select which of three options began with the same initial sound (e.g., moon starts with /m/ which one starts with /m/ pig, ball, or mouse?). The percent correct for each domain was computed, and the score for each domain averaged to create a total score (Cronbach's α = .76).

Executive Function

Working memory was assessed using the forward digit span. Children were asked to repeat sequences of numbers in the same order they were heard. The task increased in difficulty by adding one digit to each subsequent sequence (7 items). Cognitive flexibility was measured using an adapted version of the Dimensional Change Card Sort–Border version (Zelazo, 2006; 12 items). Children sorted cards based on either shape or colour. In the border version of the task, the sorting rule was by the presence or absence of a border around the card. Inhibitory control was assessed using an adapted version of the Number Stroop Task. In this task, children are shown a set of boxes with one to four repeating numbers (e.g., 1111, 44) and are asked to report how many numbers are in each box (see Obradović et al., 2019; 21 items). Finally, reaction time was assessed using the executive function Touch Bubbles Task, which was adapted to the Kenyan context (see Willoughby et al., 2019; 20 items) and piloted in Ghana. In this task, a series of blue bubbles was presented on a tablet, one at a time, and children were instructed to "pop" each bubble as fast as they could. The mean reaction time across all correctly answered items was used to index simple reaction time. To create an overall executive function score, the proportion correct for each domain was computed (Cronbach's α = .45 for the composite executive function score).

Socio-emotional Skills

Socio-emotional skills were measured using IDELA subscale (Pisani et al., 2018) with 14 items grouped into five constructs: self-awareness, emotion identification, perspective taking and empathy, friendship, and conflict and problem solving. For example, children were asked to identify something that makes them sad, what they do to feel better when they are feeling sad, and lastly, what makes them feel happy. They were also shown a picture of an upset girl and were told to imagine that the girl was his/her friend and to identify how the girl in the picture is feeling. They were next asked how they would help her feel better and whether there is anything else they would do for her. Participants could obtain a score up to three. In the sharing and solving conflict assessment, participants were told that they have one toy but another child wants to play with it, what would they do? Participants get a score depending on whether they provided a response indicating that they would share (2) or avoided conflicts (1) or provided an inappropriate response (0) Participants could obtain a maximum score of 6. Socio-emotional skills are defined as the mean percent correct across subtests (Cronbach's α = .67).

Symbolic and Non-symbolic Numerical Magnitude Processing

Symbolic and non-symbolic numerical magnitude processing were assessed using the Numeracy Screener. Children were presented a booklet with pairs of either single-digit numerals (e.g., symbolic) or dot arrays (non-symbolic) and asked to cross out the numerically larger quantity as quickly and accurately as possible. They were given one minute for each condition. The side of the larger magnitude was counterbalanced across trials. In the non-symbolic condition, density and area was controlled across trials. To control for area and density, half of the trials were equated for total surface area, and the other half were equated for total perimeter. Many studies have found that dot discrimination is influenced by the visual-spatial parameters of the stimuli. Therefore, to minimize reliance on such visual spatial cues, the sizes of the dots were heterogeneous within each array, and the order of perimeter-matched and area-matched trials were administered in a random set sequence. The order of stimuli varied slightly across conditions so that the order of presentation was not identical; however, they both began with easier pairs (small ratio; calculated small number: large number) and got increasingly more difficulty by increasing the ratio between the pairs. Half the participants completed the symbolic condition first followed by non-symbolic comparison and vice versa. The Cronbach's for the non-symbolic and symbolic conditions respectively is α = .89 and α = .90. Test-retest reliability has been previously reported in Hawes et al., (2019). The correlation for symbolic comparison (r =.72) and non-symbolic comparison (r =.61) when tested on average 89.55 days apart (Hawes et al., 2019). Test-retest reliabilities are similar to the SYMP test (Brankaer et al., 2017) Raw scores were the total number of correct trials completed within one minute for the symbolic and non-symbolic conditions separately. We followed the procedure applied in Lyons et al., (2018) to compute an adjusted score in order to account for guessing in a timed assessment (Rowley & Traub, 1977). The following formula was used to calculate the adjusted scores where C is the total number of items correct, E is the total number of errors and T is the total number of trials in the assessment $Adj = C - E/(T-1)$. Mean adjusted scores are reported in Figure 1.

Procedures

Data come from an impact evaluation study of the Quality Preschool for Ghana project (Author citation redacted), which tested the impacts of a teacher in-service training and parental-awareness program in six districts in the Greater Accra Region of Ghana. In the summer of 2015, schools (*n* = 240) were randomly assigned to one of three treatment arms: (a) Teacher training and coaching (82 schools), (b) Teacher training and coaching plus parental awareness meetings (79 schools), and (c) control group (79 schools). Impacts of the program have been presented in other papers (Author citation redacted). In this study, we use data from the third follow-up collected in June 2018.

All schools in the six districts were identified using the Ghana Education Service Educational Management Information System (GES-EMIS) database, which listed all registered schools in the country. Eligible schools had to be registered with the government and have at least one KG class. Schools were randomly sampled from the list, stratified by district and within districts by public and private schools. A school census was then conducted to confirm the presence of each school and to obtain information on each school's head teacher and proprietor. Because there were fewer than 120 public schools across the six districts (*n* = 108), every public school was sampled. Private schools (490 total) were sampled within districts in proportion to the total number of private schools in each district relative to total for all districts (*n* = 132).

Children were then sampled within each school. Class rosters for all KG classrooms were collected, and an average of 15 children (eight from KG1, and seven from KG2) were randomly selected from each roster to participate in direct assessments. If a school had fewer than 15 kindergarten children enrolled across both classrooms, all children were selected. For schools with only one KG classroom, 15 children were randomly sampled from the classroom. At baseline, the total sample of children was 3,435 children, with an average of 14.3 children per school (*range* = 4–15). Children (49.5% female) were, on average, 5.2 years-old at baseline (*SD* = 1.2; For KG1, *M* = 4.8, *SD* = 1.1; and for KG2, *M* = 5.7, *SD* = 1.2). These children were followed at each subsequent wave of data collection. At the three-year follow-up (*n* = 2,421), children were on average 7.8 years old. In this study, a random sub-sample of the three-year follow up was selected, stratified by treatment status, and administered the Numeracy Screener. All assessments were administered directly to children in their school. Data collectors were trained for five days and two additional days of field practice. They were from the local communities and spoke the local language. Assessments were translated and administered in their local language.

Analysis Plan

Frequentist statistics were carried out using R statistical software, and Bayesian statistics were carried out using Jasp (V 0.18.3). Across both studies, initial *t*-tests and bivariate correlations were conducted to examine differences in performance between the symbolic and non-symbolic conditions of the Numeracy Screener, as well as their associations with our measures of math, literacy, socio-emotional, and executive function skills. Bayesian statistics are reported for bivariate correlations and *t*-tests to evaluate the relative strength for or against the observed associations or differences (Lakens et al., 2020). Bayes factor (BF_{10}) is a ratio of the likelihood of data fitting the alternative hypothesis relative to the null hypothesis (BF_{01} is the inverse and provides support for the null relative to the alternative hypothesis). We conducted a series of multiple regression analyses to test our main research question examining the unique associations between symbolic and non-symbolic magnitude processing and math performance (model 1) while accounting for socioemotional (model 2), literacy (model 3) and executive function (model 4) skills. Gender was included as a covariate in all models. Next, we conducted multiple regression analyses to test the unique contributions of symbolic and non-symbolic magnitude processing to performance on each of the individual subtests from the EGMA controlling for socio-emotional, literacy, and executive functioning skills. We pre-registered and repeated the same analyses for Study 2 that was conducted in Côte d'Ivoire to examine the generalization of the results in Ghana.

Results

Descriptive statistics, Pearson correlations, and Bayes factors of the raw scores across all dependent measures administered in Ghana are reported in Table 1. In order to test whether there were performance differences between the symbolic and non-symbolic comparison tasks from the Screener, we conducted paired samples t-tests, and found that children from Ghana were significantly more accurate in symbolic comparison ($M = 23.43$) relative to non-symbolic comparison ($M = 22.21$), $t(349) = 3.39$, $p = .0008$, 95% CI [.51, 1,91], $d = .18$, $BF_{10} = 16.5$ (see Figure 1a). Bayes factor demonstrates that differences in accuracy between symbolic and non-symbolic comparison tasks are 16.5 times more likely than finding no difference in accuracy.

As seen in Table 1, we found significant positive associations between the adjusted scores of the Numeracy Screener and school readiness measures of math, socio-emotional, literacy, and executive functioning skills. Bayesian correlation analyses resulted in Bayes factors that are greater than 150 which according to Jeffreys (1986) criteria, provides strong evidence for the association between Numeracy Screener scores and our school readiness measures. In particular, we found that non-symbolic comparison, $r(348) = .53$, and symbolic comparison, $r(348) = .33$, significantly correlated with composite math score calculated from the EGMA (see Figure 2ab). A Steiger's test revealed that the correlation between non-symbolic number comparison and math composite scores was significantly stronger than the correlation between symbolic comparison and math composite scores, $z = 6.2$, $p < .0001$.

Table 1. *Descriptive statistics, Bivariate Correlation Matrix, and Bayes Factors*

Study 1 in Ghana													
		Mean	***SD***	***Skew***	***Kurt***		***1***	***2***	***3***	***4***	***5***	***6***	***7***
1	Numeracy Screener	45.67	17.37	.05	-.26	*r*		.93**	.93**	.46**	.39**	.26**	.30**
						95% CI		.92, 95	.92, .95	.38, .54	.30, .47	.16, .36	.20, .39
						BF10		∞	∞	1.09e17	1.13e11	1.26e4	7.78e5
2	Symbolic	23.43	9.23	-.15	-.46	*r*			.74**	.33**	.28**	.20**	.20**
						95% CI			.67, .78	.25, .43	.18, .37	.11, .31	.11, .31
						BF10			1.12e59	3.932e7	6.87e4	60.70	92.71
3	Non-symbolic	22.21	9.38	.28	.23	*r*				.53**	.45**	.29**	.36**
						95% CI				.45, .60	.36, .53	.19, .38	.26, .44
						BF10				9.29e23	2.66e15	2.42e5	1.06e9
4	Math (EGMA)	.49	.17	-.32	-.40	*r*					.71**	.36**	.51**
						95% CI					.65, .76	.26, .45	.43, .58
						BF10					2.47e51	1.23e9	2.6e21
5	Literacy	.53	.17	-.45	-.49	*r*						.40**	.49**
						95% CI						.31, .49	.40, .56
						BF10						9.12e11	1.18e19
6	Socio-emotional	.66	.14	-.64	.36	*r*							.31**
						95% CI							.21, .40
						BF10							2.84e5
7	Executive Function	.69	.09	-.18	.70								

Note. *M* = mean, *SD* = standard deviation, Skew = skewness, Kurt = kurtosis, CI = confidence interval. Literacy, Socio-emotional and Executive function skills are mean percent correct. $p < .0023$** Bonferroni corrected significance; $p<.01$*; $p<.05^{\dagger}$. BF_{10} = Bayes factor in support of the alternate hypothesis over the null. BF_{10} between 0 – 3 is weak evidence in support of an association. BF_{10} between 3 and 20 is positive support for an association. BF_{10} between 20 and 150 is strong support for an association. $BF_{10} > 150$ is very strong evidence in favor of an association (Jeffreys, 1961).

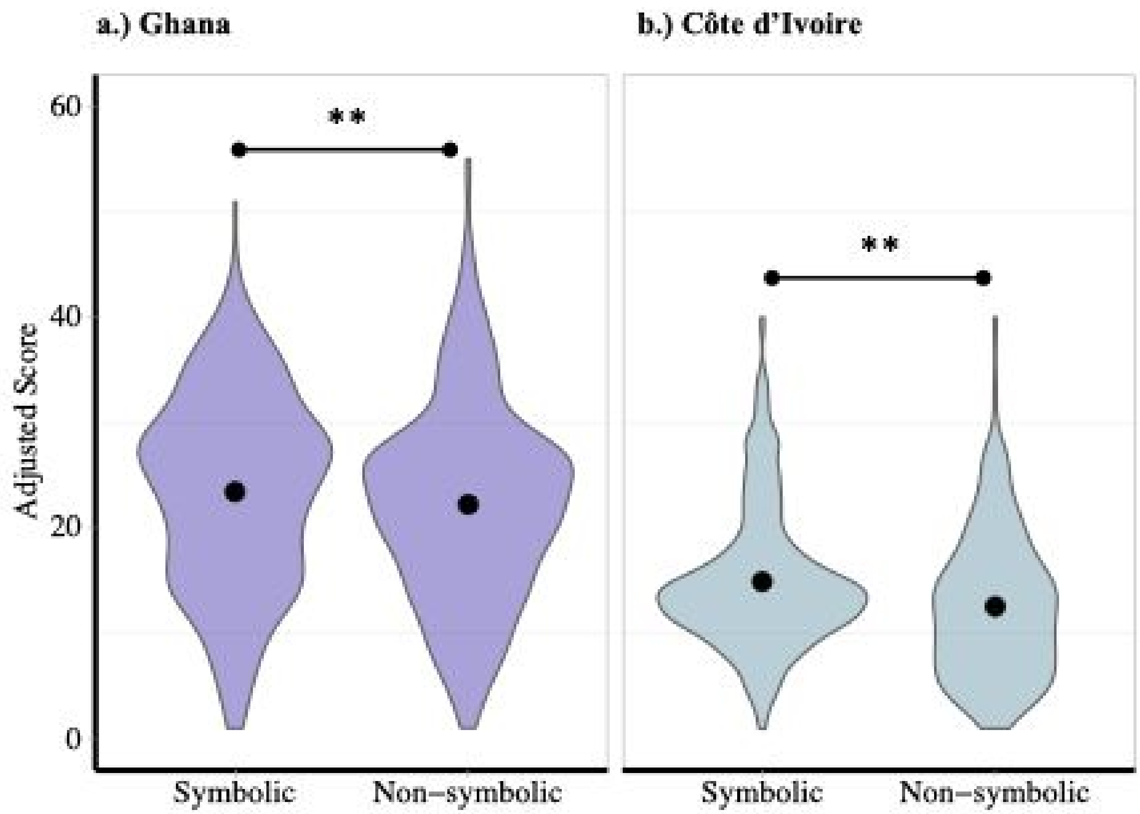

Figure 1. Mean symbolic and non-symbolic comparison adjusted scores in the sample of children from (a) Ghana and (b) Côte d'Ivoire.

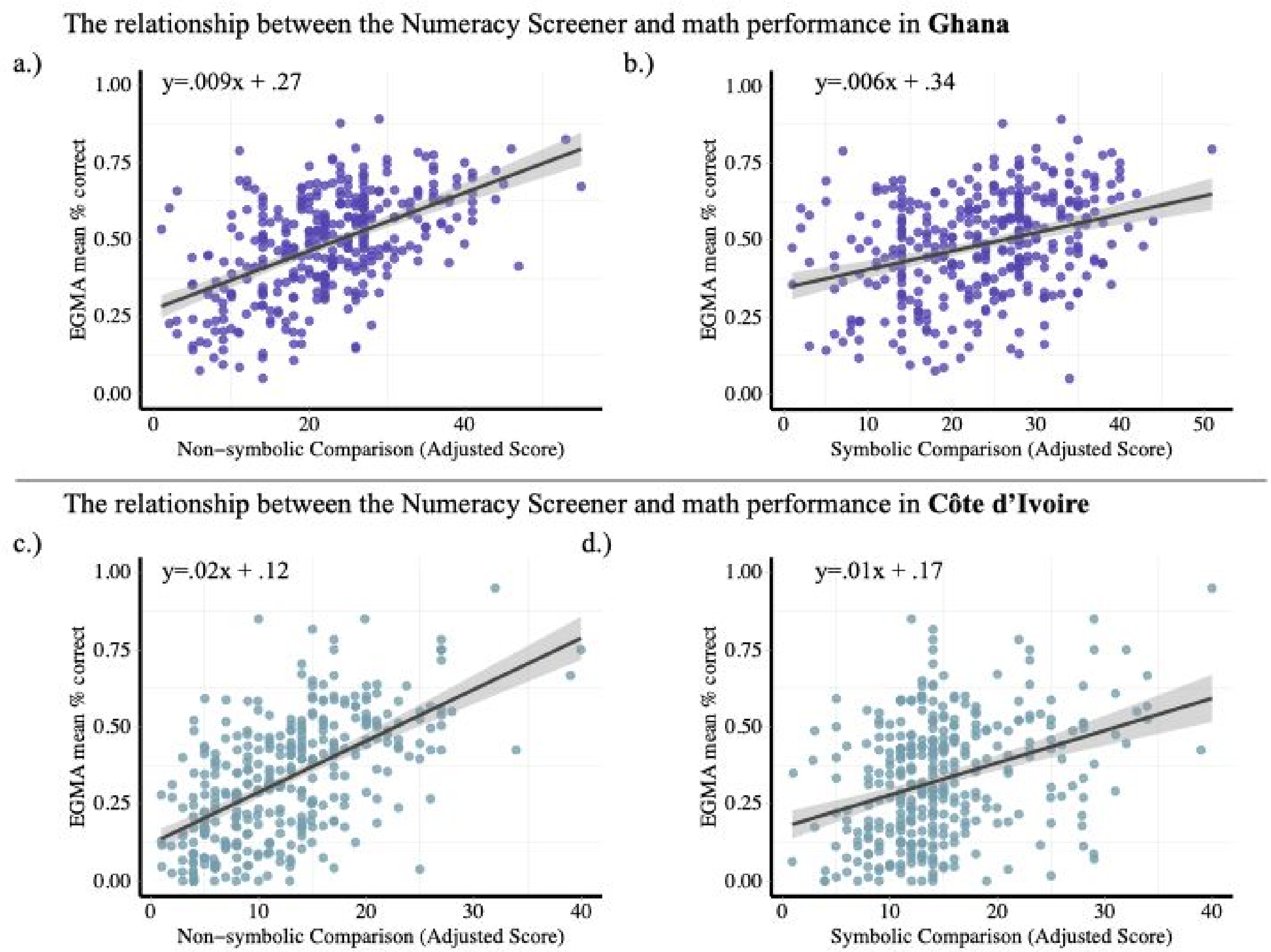

Figure 2. Scatterplots of the relationship between non-symbolic (a) and symbolic number comparison (b) adjusted scores and mean percent correct on the EGMA in the *Ghana* sample. Scatterplots showing the relationship between non-symbolic (d) and symbolic number comparison (d) adjusted scores and mean percent correct on the EGMA in *Côte d'Ivoire* sample. *Note. In Ghana the mean percent correct was calculated across all subtests administered from the EGMA including Missing Number, Number Identification, Addition, Subtraction, Word Problems, and Quantity Comparison. In Côte d'Ivoire the mean percent correct was calculated across a subset of the subtests from the EGMA: Missing Number, Number Identification, Addition and Subtraction.*

The Unique Associations between Symbolic and Non-symbolic Comparison and Math Performance

We found that performance on both subtests of the Numeracy Screener significantly correlated with all of our measures of school readiness. To test the unique association between non-symbolic numerical magnitude processing and math abilities, we ran a series of hierarchical regression analyses to control for symbolic numerical processing (step 1), socio-emotional (step 2), literacy (step 3), and executive function skills (step 4) in children from Ghana. In the first model, we first tested whether symbolic and non-symbolic comparison accounted for unique variance in math abilities (model 1). Contrary to our hypotheses, based on the results from Canada, we found that non-symbolic number comparison was the only variable that accounted for significant unique variance in math performance (see Table 2). Symbolic and non-symbolic comparison from the Numeracy Screener account for 28% of the variance in math composite scores. We next tested whether the association between non-symbolic comparison performance and math ability remained significant when accounting for the variance associated with socio-emotional skills (model 2), literacy skills (model 3) and executive function skills (model 4). Even when controlling for individual differences in socio-emotional, literacy, and executive function skills, non-symbolic comparison accounted for significant unique variance in math abilities (see Table 2). In other words, more proficient non-symbolic magnitude skills were associated with higher math composite scores, even when controlling for symbolic number processing, socio-emotional, literacy, and executive functioning skills. We also found that literacy and executive functioning skills were significant positive unique correlates of math performance. Notably, non-symbolic, literacy and executive functioning skills remained significant correlates after controlling for age in the subset of children for whom age data were available (see Supplementary Analysis 1 in the Supporting Information).

Table 2. *Multiple regression analyses predicting symbolic math abilities*

Variable	**Models predicting EGMA Scores in Ghana**			**Models predicting EGMA Scores in Côte d'Ivoire**		
Model 1	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.30***	.02		.10***	.02	
Male	-.01	.02	-.04	.03	.02	.08
Non-symbolic	.01***	.001	.63***	.02***	.002	.57***
Symbolic	-.003	.001	-.14*	.000	.002	.02
R²		.29			.35	
Adjusted R²		.28			.34	
***F*(df)**		46.95 (3, 344)**			59.38 (3, 338)***	
Model 2	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.16***	.04		.02	.03	
Male	-.01	.02	-.02	.03*	.02	.09*
Non-symbolic	.01***	.001	.57***	.02***	.002	.51***
Symbolic	-.002	.001	-.13*	.000	.002	.02

Socio-emotional	.25***	.05	.22***	.15***	.03	.22***
R^2		.33			.39	
Adjusted R^2		.33			.38	
***F*(df)**		43.04 (4, 343)***			53.86 (4, 337)***	
Model 3	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.06	.03		.06*	.02	
Male	.003	.01	.008	.03*	.02	.08*
Non-symbolic	.006***	.001	.32***	.009***	.001	.30***
Symbolic	-.001	.000	-.07	.001	.001	.04
Socio-emotional	.06	.05	.05	.03	.03	.04
Literacy	.55***	.04	.57***	.62***	.06	.49***
R^2		.57			.54	
Adjusted R^2		.56			.53	
***F*(df)**		88.77 (5, 342)***			79.05 (5, 336)***	
Model 4	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	-11*	.05		-.02	.03	
Male	.006	.01	.02	.03*	.01	.09*
Non-symbolic	.005***	.001	.28***	.008***	.001	.28***
Symbolic	-.001	.001	-.06	.000	.001	.02
Socio-emotional	.04	.04	.04	.01	.03	.02
Literacy	.49***	.04	.51***	.53***	.06	.42***
Executive Function	.32***	.08	.16***	.24***	.07	.17***
R^2		.58			.56	
Adjusted R^2		.58			.55	
***F*(df)**		79.73 (6, 341)***			70.73 (6, 335)***	

Note. *p <.05; **p <.01; ***p <.001. *In Ghana the mean percent correct was calculated across all subtests administered from the EGMA including Missing Number, Number Identification, Addition, Subtraction, Word Problems, and Quantity Comparison. In the Côte d'Ivoire the mean percent correct was calculated across the subtests administered from the EGMA including Missing Number, Number Identification, Addition, and Subtraction.*

The Relationship Between the Symbolic and Non-Symbolic Comparison and Individual Subtests from the EGMA

To further probe the nature of the association between performance on the non-symbolic comparison task and symbolic math abilities, we next tested whether individual differences in non-symbolic and symbolic number comparison accounted for unique variance in predicting individual subtest scores from the EGMA. We were also interested in testing whether the symbolic number comparison task accounted for unique variance in particular subtests of the EGMA. We ran multiple regression analyses with each subtest as the dependent measure. We included literacy, socio-emotional, and executive function skills as covariates in the models. Non-symbolic comparison accounted for unique variance in quantity discrimination, addition, and subtraction performance. Symbolic comparison performance accounted for significant unique variance in word problem solving skills. Neither symbolic or non-symbolic comparison performance accounted for unique variance in performance on the Missing Number subtest (see Table 3). We also found that literacy skills significantly predicted performance on all math subtests in the EGMA, while executive functioning skills significantly account for unique variance in the Missing Number, Addition, Subtraction, and Word Problem Solving subtests from the EGMA. A closer examination of the standardized beta coefficients revealed that literacy followed by non-symbolic comparison skills were the strongest predictors of most subtests, except for the Subtraction and Word Problems subtests. Non-symbolic comparison performance was the strongest predictor of subtraction skills. Symbolic comparison performance was a significant correlate of word problem solving skills while non-symbolic comparison was not.

Table 3. *The unique associations between symbolic and non-symbolic comparison and individual subtests from the Early Grade Math Assessment in Ghana.*

Variable	**Numeral Identification**			**Missing Number**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.13	.08		-.12**	.01	
Male	-.008	.02	-.02	-.000	.02	-.000
Non-symbolic	.004**	.002	.18**	.004*	.001	.13*
Symbolic	-.002	.001	-.06	-.001	.001	-.06
Socio-emotional	.01	.07	.01	.000	.06	.000
Literacy	.76***	.06	.58***	.45***	.06	.42***
Executive Function	.18	.12	.07	.24*	.11	.11*
R^2		.48			.32	
Adjusted R^2		.47			.31	
***F*(df)**		53.16 (6,341)***			27.12 (6, 341)***	
Variable	**Addition**			**Subtraction**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	-.27***	.08		-.36***	.07	
Male	-.01	.02	-.01	.01	.02	.02
Non-symbolic	.01***	.002	.30***	.01***	.001	.33***

Symbolic	-.002	.001	-.09	-.003*	.001	-.15*
Socio-emotional	-.01	.07	-.01	.07	.06	.06
Literacy	.46***	.07	.37***	.33***	.06	.30***
Executive Function	.50***	.12	.20***	.49***	.11	.22***
R^2		.41			.39	
Adjusted R^2		.40			.38	
***F*(df)**		40.19 (6, 341)***			36.77 (6, 341)***	
Variable	**Quantity Discrimination**			**Word Problem Solving**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.14	.10		-.20*	.08	
Male	.03	.02		.02	.02	.04
Non-symbolic	.01**	.002	.23**	.002	.002	.10
Symbolic	-.002	.002	-.08	.004*	.001	.17*
Socio-emotional	-.02	.08	-.01	.19**	.07	.14**
Literacy	.73***	.08	.49***	.24***	.07	.21***
Executive Function	.21	.15	.07	.27*	.13	.12*
R^2		.39			.27	
Adjusted R^2		.37			.26	
***F*(df)**		35.54 (6, 341)***			20.82 (6, 341)***	

Note. $*p < .05$; $**p < .01$, $***p < .001$

Discussion

In the present study, we examined the associations between symbolic and non-symbolic magnitude processing and math skills in school children from Ghana. Based on prior findings from Canada and Iran (Hawes et al., 2019; Nosworthy et al., 2013; Tavakoli, 2016), we hypothesized that symbolic comparison performance would be a stronger predictor of math performance relative to non-symbolic comparison. Contrary to our expectations, we found that non-symbolic comparison was a stronger predictor of math performance. To test the robustness of this finding, and its generalization, we subsequently conducted a pre-registered study in Côte d'Ivoire - Ghana's neighbor to the west (For the preregistration see: https://osf.io/y32d8/?view_only=1f0c09263e9c462b8a589876c2d6f8b7). Using essentially the same tasks and methods (subtle differences are discussed below in the methods), we test the hypothesis that non-symbolic comparison is a stronger predictor of math performance in Côte d'Ivoire.

Study 2 in Côte d'Ivoire

Methods

Participants

354 second grade children were tested in Côte d'Ivoire, West Africa. Children were excluded if they had a score of 0 on either the symbolic or non-symbolic conditions of the screener (n=12). A total of 342 children (female, n = 184, male, n = 158) were included in the final data analyses. (NOTE: we do not have age data here; all children were enrolled in CP2, which is the equivalent of second grade, or primary 2). Children have received one year of formal schooling prior to data collection.

Materials

Math skills

Children's math skills were assessed using eight tasks. Four tasks from the Early Grade Math Assessment (EGMA; RTI International, 2009a), which included Number Identification, Addition, Subtraction, and Missing Number subtests described above. Administration of the EGMA was the same across both the Ghana and CIV samples, however, there were some differences in the individual items in the subtests. In addition, four tasks from the IDELA (Pisani et al., 2018) were administered to assess number knowledge, one-to-one correspondence, shape identification, and sorting abilities based on color and shape. The percent correct for each domain was computed, and the score for each domain averaged to create a total score (Cronbach's α = .86)[2]. The math readiness scores in the CIV sample was computed using the same subtests that were administered in Ghana. A mean percent correct score was computed across the Number Identification, Addition, and Missing Number subtests from the EGMA.

Literacy Skills

Literacy skills in French were assessed using eight tasks measuring pre-literacy and literacy domains from two sources. Using the Early Grade Reading Assessment (EGRA; RTI International, 2009b), domains included letter-sound identification, nonword decoding, and word reading. Four additional adapted subtasks from EGRA were used and included phonological awareness, phoneme segmentation, synonyms and antonyms (Ball et al., 2022; Jasińska et al., 2022). Finally, one additional

[2] We pre-registered that math readiness scores for the CIV sample would be computed using the Numeral Identification, Addition, Subtraction, and Word Problem subtests. However, pilot testing in CIV revealed that the Word Problems subtest from the EGMA was too difficult for children and therefore, it was not administered in our sample. The Missing Number subtest was administered instead and was included in the math composite score.

measure of phonological awareness from the International Development and Early Learning Assessment (IDELA; Pisani et al., 2018) was also included. The percent correct for each domain was computed, and the score for each domain averaged to create a total score (Cronbach's α = .85).

Executive Function

Two executive functioning domains were assessed: cognitive flexibility was assessed using a tablet-based Hearts and Flowers task (Diamond et al., 2007; α = 0.86). Short-term memory was measured using a visual digit span, where children were shown 13 series of numbers ranging from two to seven digits and asked to write down the numbers they saw in the same order after each series was presented (Finch et al., 2022) (Cronbach's α = .79).

Social-emotional Skills

Socio-emotional skills were measured using IDELA subscale (Pisani et al., 2018) The same subtests that were administered in Ghana were also administered in Côte d'Ivoire (Cronbach's α = .62).

Symbolic and Non-symbolic Numerical Magnitude Processing

The instructions for the Numeracy Screener administered in the Côte d'Ivoire were translated and administered in French (Lafay et al., 2018).

Procedures

Data for this study come from the EduqPlus intervention study conducted in 100 schools in the Aboisso and Bouaflé regions of Côte d'Ivoire (Author citation redacted)**.** This school-randomized control trial examined impacts of a text-message based intervention to parents and teachers related to educational engagement and improvement**.** Fifty public schools within each region (N = 385 in Aboisso, 612 in Bouaflé) were selected by the district education office to participate in the study. Schools were randomly assigned to (i) receive the Eduq+ intervention administered to caregivers and teachers (n = 50), or (ii) a control group (n = 50).

In each school, the class rosters of CP2 (equivalent to primary 2) were obtained. Thirteen children were randomly chosen from the roster and data collected in the schools in the fall (November 2018; beginning) and spring (June 2019; end) of the school year. At follow-up, data was collected on 2,246 (89.84%) of those children. A random sub-sample, stratified by treatment status, was selected and administered the Numeracy Screener at follow-up. All assessments were administered directly to children in their school. Data collectors were trained for five days and two additional days of field practice.

Results

Descriptive statistics, Pearson correlations, and Bayes Factors of the raw scores across all dependent measures administered in Côte d'Ivoire (CIV) are reported in Table 5. We found significant positive associations between the adjusted scores of the Numeracy Screener and school readiness measures of math, socio-emotional, literacy, and executive functioning skills (see Table 5). Bayesian correlation analyses resulted in Bayes factors that are greater than 150 providing very strong evidence for the association between Numeracy Screener scores and school readiness measures (Jeffreys, 1986). One exception was that the association between symbolic comparison and socio-emotional skills failed to reach significance once Bonferroni correction was applied ($BF_{10} = .51$). These results are consistent with those reported in Ghana further showing that early numeracy skills are related to a broad range of school readiness measures in CIV. Paired samples *t*-test and Bayesian analyses revealed strong evidence to support that children from CIV are more accurate on the symbolic comparison ($M = 14.90$) relative to non-symbolic comparison task ($M = 12.53$), $t(341) = 7.14$, $p < .0001$, $d = .39$, 95% CI [1.71, 3.02], $BF_{10} = 1.03e+9$ (see Figure 1b). Adjusted non-symbolic and symbolic comparison scores significantly correlated with math performance (non-symbolic: $r(340)=.58$, $p < .0001$, and symbolic: $r(340)=.35$, $p < .0001$, see Figure 1c and d respectively). We replicated the finding that the relationship between non-symbolic comparison and math composite scores was significantly stronger than the correlation between symbolic comparison and math composite scores in the CIV sample, $z = 5.75$, $p <.0001$.

Table 5. *Descriptive statistics, Bivariate Correlation Matrix, and Bayes Factors*

Study 2 in Côte d'Ivoire													
		Mean	***SD***	***Skew***	***Kurt***		***1***	***2***	***3***	***4***	***5***	***6***	***7***
1	Numeracy Screener	27.43	11.97	.96	1.26	*r*		**.89****	**.89****	**.53****	**.44****	**.20****	**.40****
						95% CI		.86, .91	.87, .91	.45, .60	.35, .52	.09, .30	.30, .48
						BF10		∞	∞	*4.50e22*	*5.30e14*	*59.46*	*2.32e11*
2	Symbolic	14.88	6.60	1.02	1.23	*r*			**.59****	**.35****	**.27****	.11†	.30**
						95% CI			.51, .65	.26, .44	.17, .37	.01, .22	.20, .39
						BF_{10}			*3.50e29*	*3.55e8*	*3.67e4*	*.61*	*3.11e5*
3	Non-symbolic	12.52	6.85	.76	.70	*r*				**.58****	**.51****	**.24****	**.41****
						95% CI				.51, .65	.42, .58	.14, .34	.32, .49
						BF_{10}				*1.43e29*	*5.12e20*	*1229.53*	*1.92e12*
4	Math (EGMA)	.33	.20	.26	-.50	*r*					**.68****	**.34****	**.53****
						95% CI					.61, .73	.24, .43	.45, .60
						BF_{10}					*3.60e43*	*8.42e7*	*5.75e22*
5	Literacy	.19	.16	1.20	1.29	*r*						**.46****	**.56****
						95% CI						.38, .54	.48, .63
						BF_{10}						*4.54e16*	*2.82e26*
6	Socio-emotional	.64	.28	-.55	-.69	*r*							**37****
						95% CI							.27, .45
						BF_{10}							*2.02e9*
7	Executive Function	.49	.14	.35	-.28								

Note. *M* = Mean, *SD* = Standard deviation, Skew = Skewness, Kurt = Kurtosis. Literacy, Socio-emotional and Executive function skills are mean percent correct. $p < .0023$** Bonferroni corrected significance; $p<.01$*; $p<.05^{\dagger}$. BF_{10} = Bayes factor in support of the alternate hypothesis over the null. BF_{10} between 0 – 3 is weak evidence in support of an association. BF_{10} between 3 and 20 is positive support for an association. BF_{10} between 20 and 150 is strong support for an association. $BF_{10} > 150$ is very strong evidence in favor of an association (Jeffreys, 1961).

The Unique Associations between the Numeracy Screener and Math Abilities

We ran a series of hierarchical regression models using the EGMA composite score calculated from the subtests administered in CIV as the dependent measure. We replicated the same pattern of results in Ghana in CIV. Non-symbolic number comparison accounted for significant unique variance in math performance even when controlling for symbolic number comparison, socio-emotional, literacy, and executive function skills (see Table 2). In contrast to prior studies (e.g., Hawes et al., 2019; Nosworthy et al., 2013; Tavakoli, 2016), we found that non-symbolic comparison, but not symbolic comparison, accounted for significant unique variance in math abilities in Ghana and CIV.

Although children in Ghana and CIV showed higher performance on the symbolic comparison task relative to the non-symbolic comparison task, they showed poor performance on the Numeracy Screener relative to first and second grade children from Canada (Nosworthy et al., 2013), and second grade boys from Iran (Tavakoli, 2016). One hypothesis for finding a stronger relationship between non-symbolic comparison and math performance is that a large portion of children in Ghana and CIV do not recognize all numerals from 1-9. However, when children who cannot recognize their numerals are removed from the analyses, the same pattern of results hold such that non-symbolic comparison performance is a significant correlate of math scores when symbolic comparison, executive function, socio-emotional and literacy skills are accounted for in the regression model (see Supplementary Analysis 2; Supplemental Figure 1 and Supplemental Table 2 in the Supporting Information).

We next tested the unique associations between symbolic and non-symbolic comparison and individual subtests from the EGMA administered to children in CIV. We found that although non-symbolic number comparison remained a consistent predictor of performance on the individual subtests from the EGMA, there were some differences in the pattern of results from what was found in the study conducted in Ghana. In contrast to the pattern of results found in Ghana, non-symbolic comparison accounted for significant unique variance in the Missing Number subtest. We additionally found that both symbolic and non-symbolic numerical abilities accounted for significant unique variance in subtraction performance (see Table 6). We pre-registered exploratory secondary analyses that do not inform nor alter the interpretations of our main conclusions. We have included them in the Supporting Information for transparency and in case they are of use to other researchers.

Table 6. *The unique associations between symbolic and non-symbolic comparison and individual subtests from the Early Grade Math Assessment in Côte d'Ivoire.*

Variable	**Numeral Identification**			**Missing Number**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.17*	.07		-.09	.06	
Male	.07*	.03	.10*	.02	.03	.03
Non-symbolic	.01***	.003	.26***	.008**	.003	.18**
Symbolic	-.002	.003	-.05	-.000	.002	-.000
Socio-emotional	.005	.06	.004	.04	.05	.04
Literacy	.66***	.13	.31***	.89***	.12	.43***
Executive Function	.35*	.14	.14*	.39**	.12	.16**
R^2		.33			.44	
Adjusted R^2		.32			.43	
***F*(df)**		27.39 (6, 335)***			44.66 (6, 335)***	
Variable	**Addition**			**Subtraction**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	-.06	.04		-.11***	.03	
Male	.03	.02	.08	.03	.01	.10
Non-symbolic	.008***	.002	.31***	.002	.001	.12
Symbolic	.002	.002	.07	.003*	.001	.14*
Socio-emotional	-.02	.03	-.02	.01	.02	.02
Literacy	.36***	.07	.31***	.20***	.05	.25***
Executive Function	.08	.07	.06	.15**	.06	.16**
R^2		.37			.28	
Adjusted R^2		.36			.27	
***F*(df)**		32.44 (6, 335)***			22.13 (6, 335)***	

Note. *p <.05; **p <.01; ***p <.001.

General Discussion

The majority of studies conducted in the Minority World have found that individual differences in symbolic magnitude processing is a stronger predictor of math achievement than non-symbolic magnitude skills. (e.g., Nosworthy et al., 2013; Schneider et al., 2017). Given these findings, researchers have downplayed the role of non-symbolic magnitudes for learning math and have suggested that symbolic magnitude knowledge is a critical foundation for successful math development (e.g., Merkley

& Ansari, 2016). However, there is a pressing need for researchers to adopt a global perspective to evaluate whether the foundations for learning math are universal. In the present studies, we examined whether the Numeracy Screener, a paper and pencil assessment of symbolic and non-symbolic magnitude processing, was associated with general math skills in children from Ghana and Côte d'Ivoire (CIV). We specifically tested the hypothesis that symbolic magnitude processing is a stronger correlate of math abilities relative to non-symbolic magnitude processing.

Contrary to our hypothesis, we found that non-symbolic magnitude processing was a stronger correlate of general math abilities than symbolic magnitude processing. Across both West African countries, we found consistent evidence to support a moderate association between non-symbolic magnitude processing and general math skills, even when controlling for symbolic magnitude knowledge, executive functioning, socioemotional, and literacy skills. Children from Ghana and CIV were more accurate on the symbolic comparison relative to non-symbolic comparison task demonstrating that the association between non-symbolic magnitude processing and math achievement was not driven by higher performance on the non-symbolic comparison task.

Our results diverge from previous studies that have used the Numeracy Screener to assess symbolic and non-symbolic magnitude processing. For example, Nosworthy et al. (2013) found that symbolic comparison performance was a unique correlate of math achievement in first through third grade Canadian children when accounting for non-symbolic magnitude, literacy, and working memory skills. Similarly, Hawes et al., (2019) found that symbolic comparison performance in Kindergarten children accounted for significant unique variance in arithmetic skills and teacher assigned math grades a year later. The symbolic comparison condition of the Numeracy Screener also showed greater sensitivity relative to the non-symbolic comparison condition in distinguishing school-aged children who demonstrated persistent low math difficulties from their typically performing peers (Bugden et al., 2020). The importance of symbolic magnitude knowledge in the development of arithmetic skills was further supported by a study conducted in Iran. Tavakoli et al., (2016) found that performance on the symbolic comparison task accounted for significant unique variance in arithmetic scores in second grade boys. Across studies showing symbolic number comparison to be a stronger correlate of math performance, closer examination of the standardized beta coefficients for the non-symbolic comparison task reveals small non-significant contributions typically ranging from -.095 - .128 (Hawes et al., 2019; Nosworthy et al., 2013; Tavakoli, 2016). In contrast, non-symbolic magnitude skills demonstrated moderate associations with symbolic math skills, with standardized beta coefficients ranging from .13 -

.60 across models conducted in Ghana and Côte d'Ivoire. The pattern of results found in West Africa also conflicts with studies that have used computerized paradigms to assess symbolic and non-symbolic magnitude processing. They also diverge from a meta-analysis showing that the association between symbolic magnitude processing and math achievement is stronger than the relationship between non-symbolic magnitude processing and math achievement (Schneider et al., 2016). Taken together, our finding that non-symbolic magnitude processing is a moderate predictor of math achievement is inconsistent from studies conducted in the Minority World showing that symbolic magnitude processing is a stronger correlate of math achievement.

It is unclear what is driving the conflicting pattern of results found across studies, and therefore, we offer several hypotheses that require further investigation to understand how context influences math development. It remains unresolved whether the approximate magnitude system is involved in learning symbolic representations of number (Sella et al., 2021; vanMarle et al., 2014), or whether it is tangentially related later in development once symbolic representations are learned (Carey & Barner, 2019). One explanation for the diverging patterns of findings across studies is that the approximate magnitude system does play a foundational role for learning math, but that the timing and duration for which it does varies across contexts. For example, our data may suggest that non-symbolic magnitude processing plays a critical role for learning symbolic math in first and second grade children in West Africa. Studies conducted in the Minority World that have failed to find support for this hypothesis could be capturing a developmental window when non-symbolic magnitudes are no longer involved. Evidence to support this idea comes from Fazio and colleagues who found that the relationship between non-symbolic magnitude processing and math performance is stronger in children younger than 6 years old. Moreover, studies have found that non-symbolic magnitude skills support the acquisition of symbolic magnitude knowledge in preschool North American children (Chu et al., 2015; vanMarle et al., 2014). One possibility is that non-symbolic magnitudes support symbolic math development earlier in development, but once children acquire symbolic representations of magnitude, through practice and experience, they begin to form stronger associations among symbols and no longer require accessing non-symbolic magnitudes. Counter evidence to this proposal is that recent findings from the Minority World have found that symbolic magnitude processing at school entry is a stronger predictor of growth in non-symbolic skills than the reverse suggesting that acquiring symbolic magnitude skills directly influences non-symbolic magnitude representations (while the converse is not true) (e.g., Kolkman et al., 2013; Lau et al., 2021; Lyons et al., 2018; Matejko & Ansari, 2016). However, because children tested have acquired some symbolic number knowledge, a microgenetic approach starting prior to children learning the meaning of number symbols is needed to fully understand when and how non-symbolic magnitudes support symbolic number acquisition. In other words, our data might support the hypothesis that non-symbolic magnitude processing plays a small role early in development and then as children acquire symbolic number and math knowledge in school, the non-symbolic system plays a less critical role. If this were the case then one might speculate that in countries where children have less experience using symbolic numbers, they rely on non-symbolic magnitudes to carry out symbolic math across a wider developmental window. Follow up studies are necessary to test whether symbolic magnitude processing becomes a stronger predictor of math performance in older children from Ghana and CIV later in development.

A second interpretation although not mutually exclusive from the first is that there are environmental factors operating at both proximal and distal levels to the child that directly or indirectly influence how children think and learn about numbers (Whitehead et al., 2024). For example, proximal factors, such as socioeconomic status and parental education, are associated with math achievement (LeFevre et al., 2009). Specifically, research conducted in Minority World countries has shown that the home learning environment prior to starting formal school is associated with future math skills, suggesting that exposure to enriched learning environment sets children up for success when they start school (Muñez et al., 2021). Cross-cultural evidence also suggests that variability in the home learning environment extends past the Minority World. For example, Susperreguy et al. (2022) found differences in the types of activities that parents engaged in with their children between Chile, Mexico and Canada. A recent study conducted in rural communities in Côte d'Ivoire found that the home environment predicted executive functions which supports the development of numeracy and literacy skills (Jasińska, et al., 2022). These findings suggest that children's experiences with number outside of school shapes how they learn about math in school. Ghanaian culture features a lot of non-symbolic representations in terms of how food products are sold. In particular, Ghana is among one of the countries in West Africa where selling by weight and standard measures is uncommon. For example, tomatoes are grouped in different quantities in bowls and baskets, leaving the buyer to estimate which grouping has more tomatoes. This practice is very common and extends to children's daily lives, particularly those who support their family work. CIV is the largest producer of cocoa in the world. However, in cocoa producing communities, there are high levels of poverty with many families surviving on $1-2 a day (Institut National de la Statistique du Ivory Coast, 2015). Many children assist their family by working in Cocoa production and therefore are spending less time in the classroom (or drop-out all together). Numeracy exposure at home, school enrollment, and attendance rates all of which affect children's math learning trajectories.

There are also distal factors, such as school quality and curriculum, that can affect how and when symbolic and non-symbolic numerical processing relate to overall math ability. We found that mean scores across both conditions of the Numeracy Screener were lower for children in CIV and Ghana relative to children from Canada and Iran. Although there have been several initiatives to improve early education in Ghana, it has been documented that children in both countries are not always attending school and therefore may receive less math instruction. Studies have also shown that children in Ghana begin learning about numbers when they start formal schooling and reports have found that children spend an average of 3.9 hours of math instruction a week (USAID, 2018). It is also the case that instructional practices are described as teacher-centered and children are viewed as passive learners. Observational studies have shown that children are taught by rote learning, copying and imitation, as well as chorus responses, and therefore, focusing on rote rehearsal (Agbenyega, 2018; Akyeampong, 2017). For example, students in the classroom will often recite the count sequence and memorize visually presented numerals. The curriculum remains prescriptive and does not allow teachers to flexibly adapt the curriculum to meet individual students' learning needs. Without opportunities to flexibly engage with symbolic number representations, children in Ghana and Côte d'Ivoire may develop surface-level understanding of symbolic numerals. For example, they know that 4 is larger than 2, and 5 is smaller than 9, knowledge that likely reflects rote learning and supports performance on symbolic comparison tasks. However, they may not be drawing on the semantic meaning of numbers to complete these tasks, nor have they had sufficient opportunities to use numbers flexibly in ways that would foster stronger and more precise representations.

In addition to non-symbolic magnitude processing, we also found that literacy and executive function skills were significant correlates of math skills in children from Ghana and CIV. Our finding showing that non-symbolic comparison remains a significant correlate of math performance when accounting for executive function skills, including inhibitory control, is consistent with previous research suggesting that non-symbolic comparison tasks capture core quantitative skills (e.g., DeWind et al., 2015; Starr et al., 2017). Across almost all models, the standardized beta coefficients were larger for literacy skills relative to non-symbolic comparison suggesting that literacy skills are an important correlate of math development. Our findings in Ghana and CIV are also consistent with a previous study conducted in CIV (Whitehead et al., 2024), as well as with findings from Minority World contexts (Vanbinst et al., 2020) demonstrating that early precursors of reading are associated with math skills suggesting that reading and math share overlapping cognitive processes (Hübner et al., 2022).

Limitations

It is important to consider several limitations when interpreting results from the present study. First, our assessment of non-symbolic magnitude processing from the Numeracy Screener includes small quantities (e.g., 1- 4) that are within the subitizing range, as well as large quantities (e.g., 5-9) that are thought to be processed using the approximate magnitude system (Feigenson et al., 2004). It is unclear the underlying cognitive mechanisms that are driving our results and future research should include assessments that separate both cognitive systems. Second, we were unable to collect accurate age data for all children in Ghana and Côte d'Ivoire, and therefore, we are unable to account for age in our regression models. Lastly, drawing conclusions based on cross-cultural and cross-study comparisons is challenging because different studies adopt different methodological approaches that may account for diverging results. A strength of our study is that we administered the same measures in both Ghana and Côte d'Ivoire, enabling us to make direct comparisons across two countries. Importantly, while the math assessments used in these studies are widely used in Majority World countries, they differ from those used in previous studies in the Minority World that also used the Numeracy Screener. We administered the EGMA whereas Minority World studies have used measures such as the Math Fluency and Calculation Subtests from the Woodcock Johnson Tests of Achievement (Nosworthy et al., 2013); teacher-assigned math grades (Hawes et al., 2019), as well as experimenter-developed single-digit (Hawes et al., 2019; Tavakoli, 2016) and double-digit addition and subtraction tasks (Tavakoli, 2016). We note that all these studies, including our own, administered a single-digit arithmetic measure. Although the assessments vary slightly, for example, in whether they were timed or untimed, the association between non-symbolic magnitude processing and arithmetic knowledge remains stronger in Ghana and Côte d'Ivoire compared to studies from the Minority World.

Implications and Future Directions

Nonetheless, our findings have important implications for the debate surrounding the relationship between symbolic and non-symbolic magnitude processing and general math competencies across development. Much of the debate has focused on whether non-symbolic magnitude processing supports symbolic math development. Counter arguments have focused on alternate cognitive explanations, such that any relationship found between non-symbolic magnitude processing and math can be explained by domain general cognitive processes (Gilmore et al., 2013; Leibovich et al., 2017; Leibovich & Ansari, 2016). Our findings suggest that contextual variability is an important consideration to understanding the dynamic associations between symbolic and non-symbolic magnitude processing and math development.

Our results may also have important educational implications. Obtaining quality education is key to break the cycle of poverty (UNESCO) and improve economic growth (World Bank, 2001). Efforts to improve early education can protect against poor health outcomes, and lead to higher economic return (Heckman, 2006). A global approach is necessary to understand how to best invest resources in early childhood programs to reduce the achievement gap between disadvantaged children and their more advantaged peers. The associations found between performance on the Numeracy Screener and math abilities suggests that this simple 2-minute paper and pencil assessment of numerical magnitude processing, has potential to be used to monitor students' progress in countries in the Majority World. Early screening is essential to identify students who are struggling to grasp fundamental skills needed to excel in school. Adopting Westernized tools and approaches might not serve all children. Here, we demonstrate that the Numeracy Screener performance strongly predicts math achievement. Trained research assistants collected the data reported in our study, future investigations are needed to evaluate whether teachers in the Majority World also report practical utility of the Numeracy Screener to assess numerical magnitude knowledge in the classroom.

Conclusions

The current study has not only revealed important insights for numerical cognition, but for the field of cognitive science and education more broadly. We present novel results showing that non-symbolic magnitude processing is a strong and unique correlate of math achievement in school children from Ghana and Côte d'Ivoire. These findings conflict with the majority of studies conducted in Minority World countries highlighting the need for researchers to adopt a global approach to understand human cognition and the role that context plays in learning. It is important for researchers to acknowledge that evidence stemming from the Minority World cannot easily be applied and implemented globally, but instead, researchers need to consider the contextual influences.

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Title:

Non-symbolic magnitude processing is a strong correlate of symbolic math skills in children from Ghana and Côte d'Ivoire

Abstract

The ability to understand and compare non-symbolic (e.g., dot arrays) and symbolic (e.g., Arabic numerals) magnitudes is a critical foundation for learning math. A meta-analysis has revealed that symbolic magnitude processing is a stronger predictor of math performance than non-symbolic, but the evidence-base is restricted almost entirely to countries in the Minority World. It is unclear how the strength of the associations between symbolic and non-symbolic magnitude processing and math performance varies across contexts. An examination of cross-national similarities and differences in foundational numeracy skills is sorely needed. In the present study, we examine the predictive nature of symbolic and non-symbolic magnitude processing, in school-aged children from Ghana (n = 350) and Côte d'Ivoire (CIV; n = 342), two West African countries in the Majority World. Contrary to prior studies from countries in the Minority World, we found that non-symbolic magnitude processing was a significant and unique predictor of math performance in 5-to-13-year-olds from Ghana. The strong association remains significant when controlling for symbolic magnitude processing, literacy, executive functioning, and socio-emotional skills. A second pre-registered study with participants from Côte d'Ivoire revealed the same pattern of results. These associations diverged from those that have been found in the Minority World, and underscore the importance of taking a global perspective for understanding the cognitive precursors for math development. The data also highlight the potential to use the Numeracy Screener to measure children's understanding of numerical magnitude in classrooms around the world.

Keywords. Numerical magnitude processing, math achievement, sub-Saharan Africa

School entry numeracy skills are strong predictors of future academic success (Duncan et al., 2007; Romano et al., 2010). Despite growing rates of children accessing school around the world (e.g., World Bank, 2018), a large portion of children from the Majority World[1] who attend school fail to learn functional numeracy skills in the first three years of primary school (Sandefur, 2018). In sub-Saharan Africa specifically, fewer than one in five children attend any formal pre-primary education (McCoy et al., 2018) thus limiting children's exposure to formal learning environments before entering first grade. With global education goals shifting from access to school to access to high quality education (United Nations, 2015), improving early numeracy skills is critical to ensure improved learning outcomes. A deeper understanding of which foundational numeracy skills support math learning across diverse contexts, including settings where children have limited access to early learning opportunities, is essential for developing equitable and contextually relevant educational interventions.

Associations between Numerical Magnitude Processing and Math Performance

Learning abstract mathematical concepts, like mental arithmetic, stems from a basic understanding of numerical magnitude expressed using non-symbolic (e.g., collection of items) or symbolic representational formats (e.g., "five" or "5"). Symbolic representations of magnitude are inventions that require direct instruction to learn; learning their meaning is a gradual and challenging process (e.g., Sarnecka & Lee, 2009; Gobel et al., 2011). In contrast, the capacity to represent and mentally combine non-symbolic magnitudes is present at birth and shared across a variety of animal species. For example, human infants, preschool children who have not received formal training, and monkeys can perform approximate calculations using non-symbolic magnitudes (Barth et al., 2005; Brannon & Terrace, 1998; Brannon, 2002; Cantlon et al., 2016; de Hevia et al., 2020; Libertus & Brannon, 2009; Mccrink et al., 2017; Pica et al., 2004; Rugani et al., 2013; Xu & Spelke, 2000). Moreover, human adults from non-industrialized societies who have limited symbolic numerical systems show similar patterns of behavioral performance when discriminating between non-symbolic magnitudes relative to adults from industrialized societies (Piazza et al., 2013; Pica et al., 2004). The

[1] Terminology varies across international studies to refer to certain countries (e.g., non-Westernized Educated Industrialized Rich and Democratic (non-WEIRD), low- and middle- income countries (LMICs), and the Global South) varies. These terms can be problematic because they can perpetuate false hierarchies and dichotomies (Draper et al., 2022); however, they can serve a purpose to highlight inequalities and under-representation in developmental psychology research. We chose to adopt terminology recommended by Draper and colleagues to use Majority and Minority World to reflect collectively groups of countries where the majority and minority of the world's population live (Alam, 2008). The term "Majority World" was coined as an alternative to terms like "Third World", aiming to reframe the perspective by emphasizing what these countries have rather than what they lack (Alam, 2008). Majority World countries are primarily in Africa, parts of Asia, and Latin America. The Minority World countries represent a small fraction of the world's population and hold a disproportionate share of global wealth. They are typically located in North America, Western Europe, Australia/New Zealand.

ability to process symbolic and non-symbolic numerical magnitudes is often assessed using comparison tasks. In such tasks, participants are presented with either two arrays of dots (non-symbolic comparison task) or two Arabic numerals (symbolic comparison task) and asked to select the numerically larger magnitude. Accuracy and reaction time data are used as indices of the underlying precision of non-symbolic and symbolic magnitude representations. ~~Several questions about whether non-symbolic representations of magnitude or the ability to access them through their symbols is more important for learning arithmetic, and whether both formats of representing numerical magnitude continue to be important once symbolic representations are fully formed.~~

Given the hierarchical nature of mathematics, a compelling theory is that non-symbolic magnitudes serve as ontogenetic and phylogenetic precursors for acquiring symbolic math skills (Dehaene, 1997; Pizza et al., 2010). According to this view, children learn the meaning of symbolic numbers by automatically mapping them onto pre-existing representations of approximate non-symbolic magnitudes. Support for this proposal comes from cross-sectional and longitudinal studies showing that children and adults who are more accurate at discriminating between non-symbolic magnitudes tend to score higher on standardized assessments of symbolic math ability (Chu et al., 2015; Feigenson et al., 2013; Halberda et al., 2008; Libertus et al., 2011). ~~However~~, Although studies have failed to find a significant association between non-symbolic magnitude processing and symbolic math performance (e.g., Holloway & Ansari, 2009; Mundy & Gilmore, 2009; Sasanguie et al., 2013). ~~It is important to note that despite these inconsistent findings regarding the relationship relation between non-symbolic magnitude processing and symbolic math,~~ Two recent meta-analyses have confirmed there is indeed a small but significant ~~relationships~~ relation between non-symbolic magnitude processing and symbolic math skills (Chen & Li, 2014; Schneider et al., 2016). Some training studies have found that children who practice comparing or computing approximate magnitudes show significant gains in symbolic math skills (e.g., Hyde et al., 2014; Park et al., 2016), suggesting ~~these data are provide evidence to suggest~~ that non-symbolic magnitude representations play a foundational and potential causal role in acquiring symbolic math.

The extent to which non-symbolic magnitudes play a role in developing formal math skills remains contentious in the field (see Leibovich & Ansari, 2016; Szűcs & Myers, 2017; Wilkey & Ansari, 2019 for reviews). For example, researchers have argued that the observed association found between non-symbolic magnitude processing and math achievement may instead reflect domain general cognitive processes, such as ~~might be due to individual differences in~~ inhibitory control (Leibovich &

Ansari, 2016; Fuhs & McNeil, 2013; Gilmore et al., 2013; but see also Starr et al., 2017) and/or visual perceptual processing of dot stimuli (Gevers et al., 2016, but see also DeWind et al., 2015). Thus, tasks assessing non-symbolic magnitude skills may tap into several component skills, undermining the claim that they isolate core numerical skills and challenges the proposal that approximate magnitude processing plays a foundational role in symbolic math development. Further challenging this claim, several training studies have failed to find a causal link between approximate magnitude processes and symbolic math performance (e.g., Bugden et al., 2021; Ferres-Forga & Halberda, 2020; Kim et al., 2018; Szkudlarek et al., 2021, including a recent meta-analysis Qiu et al., 2021).

Alternately, studies that have examined the unique contributions of non-symbolic magnitude processing and symbolic number knowledge to math development have found that, while non-symbolic skills show a weak association with symbolic math, symbolic number knowledge is a stronger predictor prompting researchers to argue for a greater emphasis on developing early symbolic number skills. ~~Moreover,~~ For example, Nosworthy et al., (2013) found that the association between non-symbolic magnitude processing, assessed using the Numeracy Screener (www.numeracyscreener.org) – paper and pencil non-symbolic and symbolic comparison tasks, and arithmetic performance was no longer significant once they accounted for other variables, such as working memory, reading, and symbolic magnitude skills. Hawes and colleagues (2019) additionally found that symbolic comparison performance assessed using the Numeracy Screener (Nosworthy et al., 2013) in Kindergarten predicted teacher assigned math grades in first grade. In contrast, non-symbolic comparison performance was not a significant predictor of math grades (Hawes et al., 2019). These studies suggest that symbolic magnitude processing skills are a stronger predictor of math abilities (relative to non-symbolic magnitude processing). This pattern of results have been corroborated in longitudinal studies showing that symbolic comparison performance at school entry are a stronger predictor of future math achievement (Xenidou-Dervou et al., 2017) and future symbolic numerical skills (Lyons et al., 2018; Matejko & Ansari, 2016) even when controlling for non-symbolic magnitude processes. Compared to the research findings on non-symbolic magnitude processing, there is stronger and consistent evidence to support the proposition that symbolic magnitude skills play a more important role in developing math abilities. However, almost all of the studies exploring whether symbolic and non-symbolic magnitude processes are foundational for developing formal math skills come from the Minority World. ~~The role of culture and education in shaping their unique relationships has received far less attention.~~ The associations between non-symbolic and symbolic magnitude representations and symbolic math development across diverse countries and contexts (i.e., diverse learning environments and situational settings; exposure to numbers in daily life) has been largely overlooked in the literature. It remains an open question the extent to which the link between non-symbolic magnitude representations and symbolic mathematics are universal across different cultures.

Symbolic and Non-symbolic Comparison Skills across Cultures

Researchers have explored whether the unique associations between non-symbolic, symbolic magnitude processing, and arithmetic skills varied in different countries. Rodic et al., (2015) collected samples in China, UK, Russia, and Kyrgyzstan. They found that symbolic comparison accounted for significant unique variance in arithmetic skills in all countries. Non-symbolic comparison performance was not a unique correlate of arithmetic performance. Similarly, Tavakoli (2016) found that symbolic comparison performance measured using the Numeracy Screener in a large sample of second grade boys from Iran was a unique correlate of speeded and non-speeded calculation skills when controlling for non-symbolic comparison performance, working memory, processing speed, and long-term memory. Consistent with the findings from Canadian samples using the Numeracy Screener (Hawes et al., 2019; Nosworthy et al., 2013), non-symbolic comparison performance was not a significant correlate of arithmetic skills. These studies suggest that symbolic magnitude skills are an important foundation for acquiring symbolic arithmetic across different cultures.

Contextual Variation in Numerical and Math Development

The majority of cross-cultural studies exploring the associations between numerical magnitude skills and math performance are carried out in high or upper-middle income countries (except for Kyrgyzstan, which is characterized by the UN has a lower-middle income country; United Nations, 2019). Research exploring the development of symbolic and non-symbolic magnitudes skills, as well their associations with math achievement are predominantly studied in the Minority World. Cross-cultural research is essential for testing whether the mechanisms underlying math development generalize beyond findings that stem from the Minority World (Henrich et al., 2010; Nielsen et al., 2017). There are ~~many~~ several lines of evidence to suggest that ~~socio-demographic, cultural, educational factors~~ socio-cultural and educational contexts may influence numerical and mathematical development. One line of evidence comes from international comparisons that have consistently found that Asian students outperform students from Europe and the United States on general numerical and mathematical tests (e.g., Imbo & LeFevre, 2009; Siegler & Mu, 2008). ~~It has been reported that these cultural differences are associated with multiple influences including cultural, language, and education.~~

~~Although~~ Beyond cross-cultural comparisons, the home math environment, which includes parents engaging in math-specific activities and dialogue with their children, as well as their attitudes and beliefs about math, is associated with children's math achievement (e.g., Daucourt et al., 2021), suggesting that children's home experiences influence math development.

The transition to formal schooling also has a significant impact on the development of arithmetic and symbolic magnitude skills independent of age-related maturational changes (Vandecruys et al., 2025). And while ~~previous research has suggested that~~ the ability to discriminate between non-symbolic magnitudes has been considered ~~is~~ universal across species and cultures (Dehaene, 1997; Pica et al., 2004); Rodic et al. (2015) ~~demonstrated~~ found that children from Russia and China outperformed children from the UK and Krgyzstan on the non-symbolic comparison task. Similarly, Piazza et al. (2013) found that ~~the~~ education level, more than age, predicted non-symbolic comparison performance in an indigene group. ~~from the amazon was more strongly associated to non-symbolic comparison performance than age. Thus,~~ Taken together, these findings provide support that culture and education ~~not only~~ ~~influences~~ shapes both non-symbolic and symbolic math development.

The broad aim of our study is to explore the associations between symbolic and non-symbolic numerical magnitude processing and general math abilities in children from two Majority World countries in West Africa, where cultural and educational contexts differ than previously studied countries, and where research is sorely lacking (Nielsen et al., 2017). ~~countries where access to early learning opportunties is limited.~~

Education in sub-Saharan Africa ~~Majority World Countries~~

~~Many children living in the Majority World are exposed to extreme poverty and poor educational quality that is associated with poor learning outcomes~~ Compared to other Majority World regions, sub-Saharan Africa has the largest proportion of children living in poverty and that are stunted, with some of the poorest learning outcomes globally (Angrist et al., 2021). Although, global progress has been made to improve early childhood educational access, ~~though~~ concerns about poor quality persist (Yoshikawa et al., 2018). ~~School enrollment in the Majority World has increased in unprecedented rates worldwide. For example,~~ Since 2000, the percentage of primary school children unenrolled in sub-Saharan Africa has declined from 40% to 22% (UIS Data Center – UNESCO Institute for Statistics). Yet, many children and adolescents within the classroom are not achieving basic numeracy and literacy skills (Sandefur, 2018). One way to improve learning outcomes is to supply teachers with feasible evidence informed screening tools for classroom so they can monitor their students' progress. Teachers who can identify gaps in their students' learning could adapt their lesson plans, and allocate already limited resources to students who need them most (Linzarini et al., 2022). The first step to achieving this goal is to examine the underlying mechanisms that support math development across ~~cultures~~ diverse socio-cultural contexts.

The Ghanaian and Ivorian Contexts

We addressed this gap in the literature by conducting two studies exploring the foundational numeracy skills important for math learning in children from two Majority World countries: Ghana (Study 1) and Côte d'Ivoire (CIV; Study 2). While our study samples come from two neighboring countries in West Africa, Ghana and CIV provide an interesting point of comparison within the West African context. In 2004, the government in Ghana adopted the National Early Childhood Care and Development Policy, which highlighted access to quality early education as central to improving ECD and learning as well as to reducing inequalities in learning outcomes. In 2007, 2 years of pre-primary education—called *kindergarten 1* (KG1; the equivalent to pre-K in the United States) and *kindergarten 2* (KG2; the equivalent to kindergarten in the United States), respectively—were added to the universal basic education system that had previously begun in the first grade of primary school. Ghana has among the highest enrollment in preprimary school across the continent, with gross enrollment at 116% and primary school gross enrollment rates at 97% (World Bank, 2024). Despite high enrollment rates among school-aged children in Ghana, learning outcomes remain slow. For instance, 70% of second grade students and 80% of fourth grade students are unable to read simple words or perform basic arithmetic problems (World Bank, 2018). Our sample in Ghana is drawn from the Greater Accra region and is urban and peri-urban, and is the most densely populated and fastest growing region in the country. It holds significant diversity in terms of economic, linguistic, and ethnic groups (Ghana Statistical Service, 2022).

On the other hand, CIV is a francophone lower-middle-income country with a similarly sized population as of 31 million (World Bank, 2024). CIV does not have a universal preprimary school system and has very low rates of preprimary school enrollment at 10.7% gross enrollment but high rates of primary school gross enrollment at 102% (World Bank, 2025). Côte d'Ivoire ranks among the bottom 30 countries globally in learning outcomes (Angrist et al., 2021), with large inequalities between urban and rural regions (PASEC, 2020). Our sample in Côte d'Ivoire is drawn from rural cocoa-farming communities in the Aboisso and Bouaflé regions of Côte d'Ivoire. Thirty eight percent of children reported working in cocoa production to support their family's economic well-being. Reports were higher among children living in rural areas (Lichand & Wolf, 2025). Higher child employment is associated with higher school drop-out rates and lower test scores (Lichand & Wolf, 2025; Sadhu et al., 2020). Among primary school children in CIV, 19% of students in Aboisso met or exceeded minimum proficiency level in reading and 18% did so in math. In Bouaflé, only 9.4% achieved minimum level in reading and 7% in numeracy. Together, these two samples from Ghana and CIV offer a valuable opportunity to examine the associations among non-symbolic and symbolic magnitude processing skills and math readiness in children from two neighbouring yet culturally distinct, West African countries.

The Current Study

Study one was an exploratory investigation to examine whether individual differences in non-symbolic and symbolic magnitude processing was associated with symbolic math performance in primary school children from Ghana. We administered the Numeracy Screener (www.numeracyscreener.org), which is an easy to use, free paper and pencil assessment tool designed to measure non-symbolic and symbolic numerical magnitude knowledge across different educational contexts. In the symbolic condition, children compared pairs of Arabic numerals (e.g., “3 and 5”) and indicated which is larger, while in the non-symbolic condition, they compared pairs of dot arrays. The Numeracy Screener has been shown to be a reliable and valid predictor of math achievement in Minority World contexts (Hawes et al., 2019; Nosworthy et al., 2013). Therefore, we examined whether performance on the Numeracy Screener was associated with performance on the Early Grade Math Assessment (EGMA; RTI, 2009a), a standardized tool developed to assess foundational math readiness skills in early primary school children, particularly in low- and middle- income country contexts. Drawing on prior findings using the Numeracy Screener (e.g., Hawes et al., 2019; Nosworthy et al., 2013), and the strong emphasis placed on symbolic magnitude knowledge for developing math skills, our exploratory hypothesis is that symbolic comparison performance would explain unique variance in math readiness scores when controlling for non-symbolic comparison performance. After completing Study 1, we conducted a second pre-registered study in Côte d’Ivoire to examine whether the pattern we observed in Ghana could be replicated in a neighbouring, but different regional and educational context.

Study 1 in Ghana

Methods

Participants

369 children from Ghana participated in the study and were in either the first or second grade of primary school. Children were removed from the final data analyses they obtained a score of 0 on either

the symbolic or non-symbolic conditions of the numeracy screener (n = 19). None of the children reached ceiling performance. The final sample included 350 children (male, n = 189, female, n = 159, unknown = 2). Accurate age data was difficult to obtain, because families do not have birth certificates or track birthdays in the same way as is typical in Western contexts. Of the 350 children, we were able to collect age information using school records for 274 participants. Children were between 5-13 years of age (M_{age} = 7.68 years, SD = 1.33). Children were sampled at the end of the school year and therefore had between 3-4 years of formal school.

Materials

Math skills

Early numeracy and arithmetic skills were assessed using The Early Grade Math Assessment (EGMA) (RTI International, 2009a). The EGMA is an oral assessment of early numeracy and arithmetic operations. The Number Identification, Quantity Discrimination, Addition, Subtraction, Word Problems, and Missing Number subtests were administered (Cronbach's α = .87). Across all subtests, if children spent more than five seconds on one item, they were asked to move onto the next trial. Administration of a subtest ended when they made four successive errors. A score was calculated by computing a mean percent correct for each subtest. Participants' math performance was calculated by computing a mean percent correct across all six math subtests.

Number Identification. The Number Identification subtest consists of 20 items that required children to identify increasingly larger single, double, and triple-digit numerals. Children were presented a card with all the numerals on it and asked to point to each number and tell the experimenter what it is. Children were given one minute to complete as many items as they could.

Quantity Discrimination. Children were presented with pairs of either single, double-, or triple-digit numerals and asked to indicate which number was bigger. They were first given two practice trials with feedback followed by 10 test trials. Five trials were shown on a stimulus card at a time. Children were given unlimited time to complete the test.

Addition and Subtraction. Children are shown a stimulus card with 10 addition problems and asked to say the answer for each problem. If they did not know the answer, they were asked to skip it and move onto the next problem. When the first 10 problems were completed, they were given the next stimulus card with 10 more problems. The addition problems increased in difficulty whereby the second half of the problems included double digit numerals. Children were given one minute to complete as many problems as they could. Participants were given paper, pencil, and counters if needed. The subtraction subtest was similar to the addition, but instead children completed subtraction problems.

Word Problems. Children were asked to solve verbally presented math story problems (e.g., There are 5 seats on the bus, there are 2 children on each seat. How many children are on the bus altogether?). Children were given two practice trials with feedback followed by six test problems. Children were given unlimited time to calculate the solution, as well as paper, pencil, and counters in case they were needed.

Missing Number. Children are presented three numerals with a space indicating a number is missing from the sequence (e.g., 1, 2 __, 4 "Here are some numbers one, two and four"), and were asked what number completes the missing part of the sequence (e.g., "What number goes here"). Single, double, and triple-digit numeral sequences were administered in increasingly more difficult order. A total of 10 test trials were administered. Five trials were presented on a stimulus card at one time. Children were given unlimited time to complete the test.

Literacy Skills

Literacy skills were measured across five domains of literacy and pre-literacy skills were measured primarily with the Early Grade Reading Assessment (EGRA; RTI International, 2009b). Children completed an oral vocabulary task where they were presented with pictures of objects and asked to name them (8 items). To assess listening comprehension, the experimenter read a short story aloud and asked the participants three questions related to its content. ~~Domains included expressive vocabulary, listening comprehension (in both English and the child's mother tongue),~~ Letter-sound identification was assessed by asking children to produce the sounds of visually presented letters. Children also completed a nonword decoding task where they presented with made-up words in English and asked to read as many as they can. Across all subtests from the EGRA, for the exception of listening comprehension, children were given 60 seconds to answer as many as items as they could correctly. A measure of phonological awareness from the International Development and Early Learning Assessment (IDELA; Pisani, Dowd, & Borisova, 2018) was also included. In this task, children were presented with a target word and asked to select which of three options began with the same initial sound (e.g., moon starts with /m/ which one starts with /m/ pig, ball, or mouse?). The percent correct for each domain was computed, and the score for each domain averaged to create a total score (Cronbach's $\alpha = .76$).

Executive Function

Working memory was assessed using the forward digit span. Children were asked to repeat sequences of numbers in the same order they were heard. The task increased in difficulty by adding one digit to each subsequent sequence (7 items). Cognitive flexibility was measured using an adapted version of the Dimensional Change Card Sort–Border version (Zelazo, 2006; 12 items). Children sorted cards based on either shape or colour. In the border version of the task, the sorting rule was by the presence or absence of a border around the card. Inhibitory control was assessed using an adapted version of the Number Stroop Task. In this task, children are shown a set of boxes with one to four repeating numbers (e.g., 1111, 44) and are asked to report how many numbers are in each box (see Obradović et al., 2019; 21 items). Finally, reaction time was assessed using the executive function Touch Bubbles Task, which was adapted to the Kenyan context (see Willoughby et al., 2019; 20 items) and piloted in Ghana. In this task, a series of blue bubbles was presented on a tablet, one at a time, and children were instructed to "pop" each bubble as fast as they could. The mean reaction time across all correctly answered items was used to index simple reaction time. To create an overall executive function score, the proportion correct for each domain was computed (Cronbach's α = .45 for the composite executive function score).

Socio-emotional Skills

Socio-emotional skills were measured using IDELA subscale (Pisani et al., 2018) with 14 items grouped into five constructs: self-awareness, emotion identification, perspective taking and empathy, friendship, and conflict and problem solving. For example, children were asked to identify something that makes them sad, what they do to feel better when they are feeling sad, and lastly, what makes them feel happy. They were also shown a picture of an upset girl and were told to imagine that the girl was his/her friend and to identify how the girl in the picture is feeling. They were next asked how they would help her feel better and whether there is anything else they would do for her. Participants could obtain a score up to three. In the sharing and solving conflict assessment, participants were told that they have one toy but another child wants to play with it, what would they do? Participants get a score depending on whether they provided a response indicating that they would share (2) or avoided conflicts (1) or provided an inappropriate response (0) Participants could obtain a maximum score of 6. Socio-emotional skills are defined as the mean percent correct across subtests (Cronbach's α = .67).

Symbolic and Non-symbolic Numerical Magnitude Processing

Symbolic and non-symbolic numerical magnitude processing were assessed using the Numeracy Screener. Children were presented a booklet with pairs of either single-digit numerals (e.g., symbolic) or dot arrays (non-symbolic) and asked to cross out the numerically larger quantity as quickly and accurately as possible. They were given one minute for each condition. The side of the larger magnitude was counterbalanced across trials. In the non-symbolic condition, density and area was controlled across trials. To control for area and density, half of the trials were equated for total surface area, and the other half were equated for total perimeter. Many studies have found that dot discrimination is influenced by the visual-spatial parameters of the stimuli. Therefore, to minimize reliance on such visual spatial cues, the sizes of the dots were heterogeneous within each array, and the order of perimeter-matched and area-matched trials were administered in a random set sequence. The order of stimuli varied slightly across conditions so that the order of presentation was not identical; however, they both began with easier pairs (small ratio; calculated small number: large number) and got increasingly more difficulty by increasing the ratio between the pairs. Half the participants completed the symbolic condition first followed by non-symbolic comparison and vice versa. The Cronbach's for the non-symbolic and symbolic conditions respectively is $\alpha = .89$ and $\alpha = .90$. Test-retest reliability has been previously reported in Hawes et al., (2019). The correlation for symbolic comparison (*r* =.72) and non-symbolic comparison (*r* =.61) when tested on average 89.55 days apart (Hawes et al., 2019). Test-retest reliabilities are similar to the SYMP test (Brankaer et al., 2017) Raw scores were the total number of correct trials completed within one minute for the symbolic and non-symbolic conditions separately. We followed the procedure applied in Lyons et al., (2018) to compute an adjusted score in order to account for guessing in a timed assessment (Rowley & Traub, 1977). The following formula was used to calculate the adjusted scores where C is the total number of items correct, E is the total number of errors and T is the total number of trials in the assessment $Adj = C - E/(T-1)$. Mean adjusted scores are reported in Figure 1.

Procedures

Data come from an impact evaluation study of the Quality Preschool for Ghana project (Author citation redacted), which tested the impacts of a teacher in-service training and parental-awareness program in six districts in the Greater Accra Region of Ghana. In the summer of 2015, schools (*n* = 240) were randomly assigned to one of three treatment arms: (a) Teacher training and coaching (82 schools), (b) Teacher training and coaching plus parental awareness meetings (79 schools), and (c) control group (79 schools). Impacts of the program have been presented in other papers (Author citation redacted). In this study, we use data from the third follow-up collected in June 2018.

All schools in the six districts were identified using the Ghana Education Service Educational Management Information System (GES-EMIS) database, which listed all registered schools in the country. Eligible schools had to be registered with the government and have at least one KG class. Schools were randomly sampled from the list, stratified by district and within districts by public and private schools. A school census was then conducted to confirm the presence of each school and to obtain information on each school's head teacher and proprietor. Because there were fewer than 120 public schools across the six districts (*n* = 108), every public school was sampled. Private schools (490 total) were sampled within districts in proportion to the total number of private schools in each district relative to total for all districts (*n* = 132).

Children were then sampled within each school. Class rosters for all KG classrooms were collected, and an average of 15 children (eight from KG1, and seven from KG2) were randomly selected from each roster to participate in direct assessments. If a school had fewer than 15 kindergarten children enrolled across both classrooms, all children were selected. For schools with only one KG classroom, 15 children were randomly sampled from the classroom. At baseline, the total sample of children was 3,435 children, with an average of 14.3 children per school (*range* = 4–15). Children (49.5% female) were, on average, 5.2 years-old at baseline (*SD* = 1.2; For KG1, *M* = 4.8, *SD* = 1.1; and for KG2, *M* = 5.7, *SD* = 1.2). These children were followed at each subsequent wave of data collection. At the three-year follow-up (*n* = 2,421), children were on average 7.8 years old. In this study, a random sub-sample of the three-year follow up was selected, stratified by treatment status, and administered the Numeracy Screener. All assessments were administered directly to children in their school. Data collectors were trained for five days and two additional days of field practice. They were from the local communities and spoke the local language. Assessments were translated and administered in their local language.

Analysis Plan

Frequentist statistics were carried out using R statistical software, and Bayesian statistics were carried out using Jasp (V 0.18.3). Across both studies, initial *t*-tests and bivariate correlations were conducted to examine differences in performance between the symbolic and non-symbolic conditions of the Numeracy Screener, as well as their associations with our measures of math, literacy, socio-emotional, and executive function skills. Bayesian statistics are reported for bivariate correlations and *t*-tests to evaluate the relative strength for or against the observed associations or differences (Lakens et al., 2020). Bayes factor (BF_{10}) is a ratio of the likelihood of data fitting the alternative hypothesis relative to the null hypothesis (BF_{01} is the inverse and provides support for the null relative to the alternative hypothesis). We conducted a series of multiple regression analyses to test our main research question examining the unique associations between symbolic and non-symbolic magnitude processing and math performance (model 1) while accounting for socioemotional (model 2), literacy (model 3) and executive function (model 4) skills. Gender was included as a covariate in all models. Next, we conducted multiple regression analyses to test the unique contributions of symbolic and non-symbolic magnitude processing to performance on each of the individual subtests from the EGMA controlling for socio-emotional, literacy, and executive functioning skills. We pre-registered and repeated the same analyses for Study 2 that was conducted in Côte d'Ivoire to examine the generalization of the results in Ghana.

Results

Descriptive statistics, Pearson correlations, and Bayes factors of the raw scores across all dependent measures administered in Ghana are reported in Table 1. In order to test whether there were performance differences between the symbolic and non-symbolic comparison tasks from the Screener, we conducted paired samples t-tests, and found that children from Ghana were significantly more accurate in symbolic comparison ($M = 23.43$) relative to non-symbolic comparison ($M = 22.21$), $t(349) = 3.39$, $p = .0008$, 95% CI [.51, 1,91], $d = .18$, $BF_{10} = 16.5$ (see Figure 1a). Bayes factor demonstrates that differences in accuracy between symbolic and non-symbolic comparison tasks are 16.5 times more likely than finding no difference in accuracy.

As seen in Table 1, we found significant positive associations between the adjusted scores of the Numeracy Screener and school readiness measures of math, socio-emotional, literacy, and executive functioning skills. Bayesian correlation analyses resulted in Bayes factors that are greater than 150 which according to Jeffreys (1986) criteria, provides strong evidence for the association between Numeracy Screener scores and our school readiness measures. In particular, we found that non-symbolic comparison, $r(348) = .53$, and symbolic comparison, $r(348) = .33$, significantly correlated with composite math score calculated from the EGMA (see Figure 2ab). A Steiger's test revealed that the correlation between non-symbolic number comparison and math composite scores was significantly stronger than the correlation between symbolic comparison and math composite scores, $z = 6.2$, $p < .0001$.

Table 1. *Descriptive statistics, Bivariate Correlation Matrix, and Bayes Factors*

Study 1 in Ghana													
		Mean	***SD***	***Skew***	***Kurt***		***1***	***2***	***3***	***4***	***5***	***6***	***7***
1	Numeracy Screener	45.67	17.37	.05	-.26	*r*		**.93****	**.93****	**.46****	**.39****	**.26****	**.30****
						95% CI		.92, 95	.92, .95	.38, .54	.30, .47	.16, .36	.20, .39
						BF10		∞	∞	1.09e17	1.13e11	1.26e4	7.78e5
2	Symbolic	23.43	9.23	-.15	-.46	*r*			**.74****	**.33****	**.28****	**.20****	**.20****
						95% CI			.67, .78	.25, .43	.18, .37	.11, .31	.11, .31
						BF10			1.12e59	3.932e7	6.87e4	60.70	92.71
3	Non-symbolic	22.21	9.38	.28	.23	*r*				**.53****	**.45****	**.29****	**.36****
						95% CI				.45, .60	.36, .53	.19, .38	.26, .44
						BF10				9.29e23	2.66e15	2.42e5	1.06e9
4	Math (EGMA)	.49	.17	-.32	-.40	*r*					**.71****	**.36****	**.51****
						95% CI					.65, .76	.26, .45	.43, .58
						BF10					2.47e51	1.23e9	2.6e21
5	Literacy	.53	.17	-.45	-.49	*r*						**.40****	**.49****
						95% CI						.31, .49	.40, .56
						BF10						9.12e11	1.18e19
6	Socio-emotional	.66	.14	-.64	.36	*r*							**.31****
						95% CI							.21, .40
						BF10							2.84e5
7	Executive Function	.69	.09	-.18	.70								

Note. *M* = mean, *SD* = standard deviation, Skew = skewness, Kurt = kurtosis, CI = confidence interval. Literacy, Socio-emotional and Executive function skills are mean percent correct. $p < .0023$** Bonferroni corrected significance; $p<.01$*; $p<.05^{\dagger}$. BF_{10} = Bayes factor in support of the alternate hypothesis over the null. BF_{10} between 0 – 3 is weak evidence in support of an association. BF_{10} between 3 and 20 is positive support for an association. BF_{10} between 20 and 150 is strong support for an association. BF_{10} > 150 is very strong evidence in favor of an association (Jeffreys, 1961).

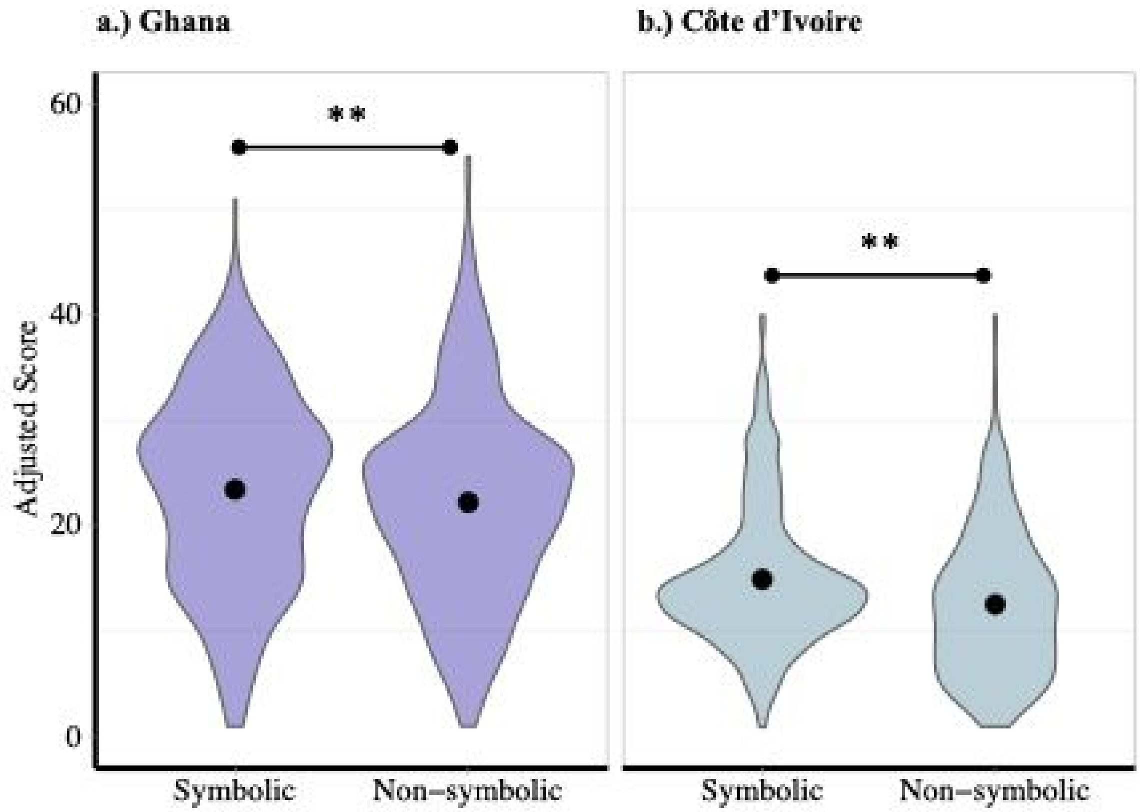

Figure 1. Mean symbolic and non-symbolic comparison adjusted scores in the sample of children from (a) Ghana and (b) Côte d'Ivoire.

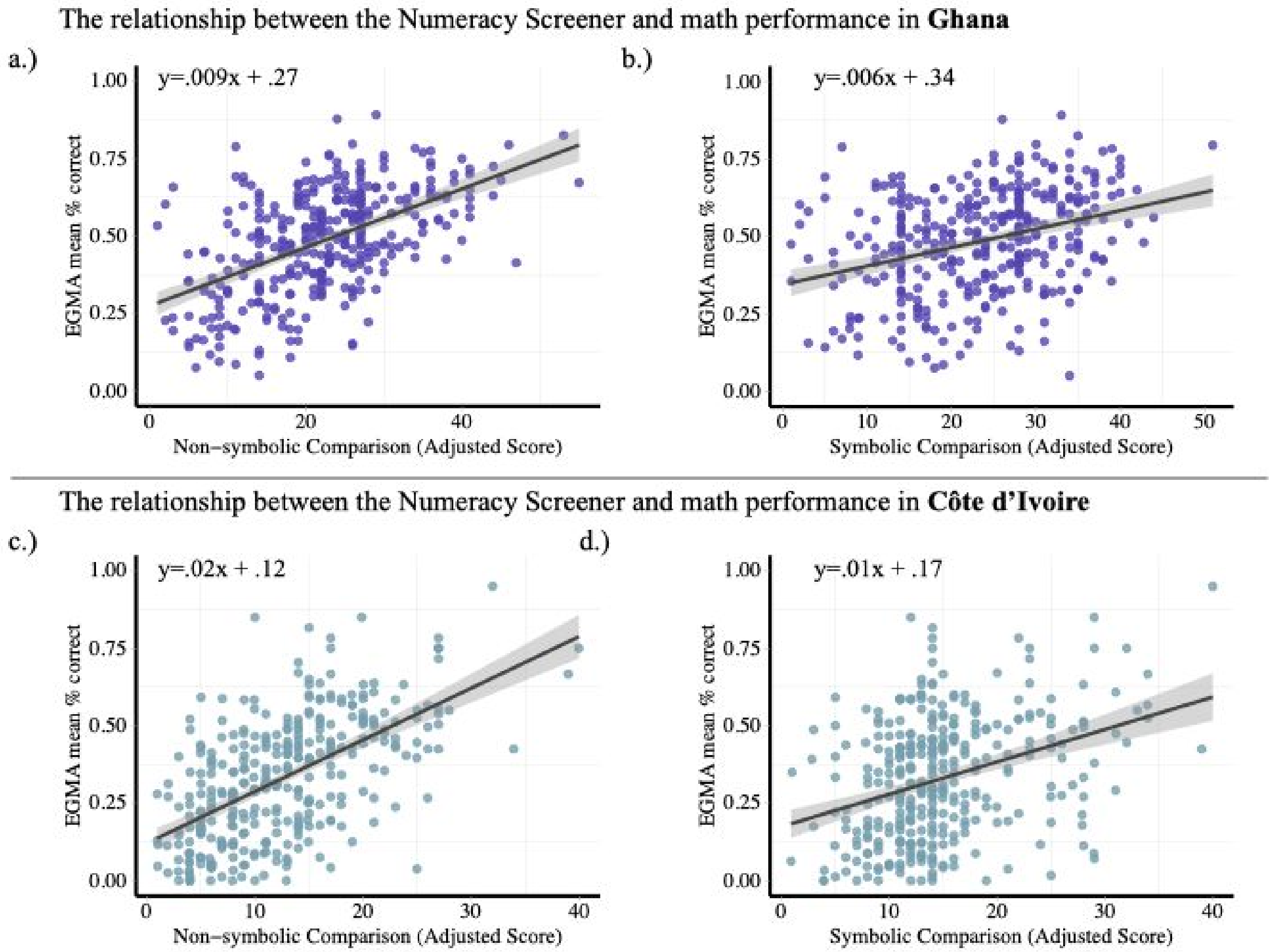

Figure 2. Scatterplots of the relationship between non-symbolic (a) and symbolic number comparison (b) adjusted scores and mean percent correct on the EGMA in the *Ghana* sample. Scatterplots showing the relationship between non-symbolic (d) and symbolic number comparison (d) adjusted scores and mean percent correct on the EGMA in *Côte d'Ivoire* sample. *Note. In Ghana the mean percent correct was calculated across all subtests administered from the EGMA including Missing Number, Number Identification, Addition, Subtraction, Word Problems, and Quantity Comparison. In Côte d'Ivoire the mean percent correct was calculated across a subset of the subtests from the EGMA: Missing Number, Number Identification, Addition and Subtraction.*

The Unique Associations between Symbolic and Non-symbolic Comparison and Math Performance

We found that performance on both subtests of the Numeracy Screener significantly correlated with all of our measures of school readiness. To test the unique association between non-symbolic numerical magnitude processing and math abilities, we ran a series of hierarchical regression analyses to control for symbolic numerical processing (step 1), socio-emotional (step 2), literacy (step 3), and executive function skills (step 4) in children from Ghana. In the first model, we first tested whether symbolic and non-symbolic comparison accounted for unique variance in math abilities (model 1). Contrary to our hypotheses, based on the results from Canada, we found that non-symbolic number comparison was the only variable that accounted for significant unique variance in math performance (see Table 2). Symbolic and non-symbolic comparison from the Numeracy Screener account for 28% of the variance in math composite scores. We next tested whether the association between non-symbolic comparison performance and math ability remained significant when accounting for the variance associated with socio-emotional skills (model 2), literacy skills (model 3) and executive function skills (model 4). Even when controlling for individual differences in socio-emotional, literacy, and executive function skills, non-symbolic comparison accounted for significant unique variance in math abilities (see Table 2). In other words, more proficient non-symbolic magnitude skills were associated with higher math composite scores, even when controlling for symbolic number processing, socio-emotional, literacy, and executive functioning skills. We also found that literacy and executive functioning skills were significant positive unique correlates of math performance. Notably, non-symbolic, literacy and executive functioning skills remained significant correlates after controlling for age in the subset of children for whom age data were available (see Supplementary Analysis 1 in the Supporting Information).

Table 2. *Multiple regression analyses predicting symbolic math abilities*

Variable	**Models predicting EGMA Scores in Ghana**			**Models predicting EGMA Scores in Côte d'Ivoire**		
Model 1	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.30***	.02		.10***	.02	
Male	-.01	.02	-.04	.03	.02	.08
Non-symbolic	.01***	.001	.63***	.02***	.002	.57***
Symbolic	-.003	.001	-.14*	.000	.002	.02
R^2		.29			.35	
Adjusted R^2		.28			.34	
***F*(df)**	46.95 (3, 344)**			59.38 (3, 338)***		
Model 2	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.16***	.04		.02	.03	
Male	-.01	.02	-.02	.03*	.02	.09*
Non-symbolic	.01***	.001	.57***	.02***	.002	.51***
Symbolic	-.002	.001	-.13*	.000	.002	.02

Socio-emotional	.25***	.05	.22***	.15***	.03	.22***
R^2		.33			.39	
Adjusted R^2		.33			.38	
***F*(df)**		43.04 (4, 343)***			53.86 (4, 337)***	
Model 3	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.06	.03		.06*	.02	
Male	.003	.01	.008	.03*	.02	.08*
Non-symbolic	.006***	.001	.32***	.009***	.001	.30***
Symbolic	-.001	.000	-.07	.001	.001	.04
Socio-emotional	.06	.05	.05	.03	.03	.04
Literacy	.55***	.04	.57***	.62***	.06	.49***
R^2		.57			.54	
Adjusted R^2		.56			.53	
***F*(df)**		88.77 (5, 342)***			79.05 (5, 336)***	
Model 4	***B***	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	-11*	.05		-.02	.03	
Male	.006	.01	.02	.03*	.01	.09*
Non-symbolic	.005***	.001	.28***	.008***	.001	.28***
Symbolic	-.001	.001	-.06	.000	.001	.02
Socio-emotional	.04	.04	.04	.01	.03	.02
Literacy	.49***	.04	.51***	.53***	.06	.42***
Executive Function	.32***	.08	.16***	.24***	.07	.17***
R^2		.58			.56	
Adjusted R^2		.58			.55	
***F*(df)**		79.73 (6, 341)***			70.73 (6, 335)***	

Note. *p <.05; **p <.01; ***p <.001. *In Ghana the mean percent correct was calculated across all subtests administered from the EGMA including Missing Number, Number Identification, Addition, Subtraction, Word Problems, and Quantity Comparison. In the Côte d'Ivoire the mean percent correct was calculated across the subtests administered from the EGMA including Missing Number, Number Identification, Addition, and Subtraction.*

The Relationship Between the Symbolic and Non-Symbolic Comparison and Individual Subtests from the EGMA

To further probe the nature of the association between performance on the non-symbolic comparison task and symbolic math abilities, we next tested whether individual differences in non-symbolic and symbolic number comparison accounted for unique variance in predicting individual subtest scores from the EGMA. We were also interested in testing whether the symbolic number comparison task accounted for unique variance in particular subtests of the EGMA. We ran multiple regression analyses with each subtest as the dependent measure. We included literacy, socio-emotional, and executive function skills as covariates in the models. Non-symbolic comparison accounted for unique variance in quantity discrimination, addition, and subtraction performance. Symbolic comparison performance accounted for significant unique variance in word problem solving skills. Neither symbolic or non-symbolic comparison performance accounted for unique variance in performance on the Missing Number subtest (see Table 3). We also found that literacy skills significantly predicted performance on all math subtests in the EGMA, while executive functioning skills significantly account for unique variance in the Missing Number, Addition, Subtraction, and Word Problem Solving subtests from the EGMA. A closer examination of the standardized beta coefficients revealed that literacy followed by non-symbolic comparison skills were the strongest predictors of most subtests, except for the Subtraction and Word Problems subtests. Non-symbolic comparison performance was the strongest predictor of subtraction skills. Symbolic comparison performance was a significant correlate of word problem solving skills while non-symbolic comparison was not.

Table 3. *The unique associations between symbolic and non-symbolic comparison and individual subtests from the Early Grade Math Assessment in Ghana.*

Variable	**Numeral Identification**			**Missing Number**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.13	.08		-.12**	.01	
Male	-.008	.02	-.02	-.000	.02	-.000
Non-symbolic	.004**	.002	.18**	.004*	.001	.13*
Symbolic	-.002	.001	-.06	-.001	.001	-.06
Socio-emotional	.01	.07	.01	.000	.06	.000
Literacy	.76***	.06	.58***	.45***	.06	.42***
Executive Function	.18	.12	.07	.24*	.11	.11*
R^2		.48			.32	
Adjusted R^2		.47			.31	
F**(df)**		53.16 (6,341)***			27.12 (6, 341)***	
Variable	**Addition**			**Subtraction**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	-.27***	.08		-.36***	.07	
Male	-.01	.02	-.01	.01	.02	.02
Non-symbolic	.01***	.002	.30***	.01***	.001	.33***

Symbolic	-.002	.001	-.09	-.003*	.001	-.15*
Socio-emotional	-.01	.07	-.01	.07	.06	.06
Literacy	.46***	.07	.37***	.33***	.06	.30***
Executive Function	.50***	.12	.20***	.49***	.11	.22***
R^2		.41			.39	
Adjusted R^2		.40			.38	
***F*(df)**		40.19 (6, 341)***			36.77 (6, 341)***	
Variable	**Quantity Discrimination**			**Word Problem Solving**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.14	.10		-.20*	.08	
Male	.03	.02		.02	.02	.04
Non-symbolic	.01**	.002	.23**	.002	.002	.10
Symbolic	-.002	.002	-.08	.004*	.001	.17*
Socio-emotional	-.02	.08	-.01	.19**	.07	.14**
Literacy	.73***	.08	.49***	.24***	.07	.21***
Executive Function	.21	.15	.07	.27*	.13	.12*
R^2		.39			.27	
Adjusted R^2		.37			.26	
***F*(df)**		35.54 (6, 341)***			20.82 (6, 341)***	

Note. $^*p$ <.05; $^{**}p$ <.01, $^{***}p$ <.001

Discussion

In the present study, we examined the associations between symbolic and non-symbolic magnitude processing and math skills in school children from Ghana. Based on prior findings from Canada and Iran (Hawes et al., 2019; Nosworthy et al., 2013; Tavakoli, 2016), we hypothesized that symbolic comparison performance would be a stronger predictor of math performance relative to non-symbolic comparison. Contrary to our expectations, we found that non-symbolic comparison was a stronger predictor of math performance. To test the robustness of this finding, and its generalization, we subsequently conducted a pre-registered study in Côte d'Ivoire - Ghana's neighbor to the west (For the preregistration see: https://osf.io/y32d8/?view_only=1f0c09263e9c462b8a589876c2d6f8b7). Using essentially the same tasks and methods (subtle differences are discussed below in the methods), we test the hypothesis that non-symbolic comparison is a stronger predictor of math performance in Côte d'Ivoire. ~~The two countries provide an interesting contrast to test and replicate our research question. Ghana is an anglophone country and has the second highest pre-primary enrollment rates in sub-Saharan Africa at 75% (UNESCO, 2015). Our sample in Ghana was enrolled in at least one year of pre-primary~~

education and at least two years of formal schooling before our assessment. Côte d'Ivoire, on the otherhand, is a francophone country with low enrollment in pre-primary education, estimated at around 8% and nearly exclusively in urban areas (World Bank, 2019).

Study 2 in Côte d'Ivoire

Methods

Participants

354 second grade children were tested in Côte d'Ivoire, West Africa. Children were excluded if they had a score of 0 on either the symbolic or non-symbolic conditions of the screener (n=12). A total of 342 children (female, n = 184, male, n = 158) were included in the final data analyses. (NOTE: we do not have age data here; all children were enrolled in CP2, which is the equivalent of second grade, or primary 2). Children have received one year of formal schooling prior to data collection. Côte d'Ivoire is a lower-middle-income West African country with a gross domestic product per capita of $3,900 and a population of 27.4 million people with a life expectancy of 61.4 years (Central Intelligence Agency, 2018). The country currently ranks 170 of 189 countries in the Human Development Index (a composite index of life expectancy, education, and per capita income) and is the largest producer of cocoa in the world. In rural cocoa-producing communities, poverty is rampant (International Monetary Fund, 2009), with many households surviving on $1-2 a day (Côte d'Ivoire Institut National de la Statistique, 2015) and an estimated 1.3 million children are engaged in child cocoa labor, which interferes with their schooling (Tulane University, 2015).

Materials

Math skills

Children's math skills were assessed using eight tasks. Four tasks from the Early Grade Math Assessment (EGMA; RTI International, 2009a), which included Number Identification, Addition, Subtraction, and Missing Number subtests described above. Administration of the EGMA was the same across both the Ghana and CDI CIV samples, however, there were some differences in the individual items in the subtests. In addition, four tasks from the IDELA (Pisani et al., 2018) were administered to assess number knowledge, one-to-one correspondence, shape identification, and sorting abilities based on color and shape. The percent correct for each domain was computed, and the score for each domain averaged to create a total score (Cronbach's α = .86)[2]. The math readiness scores in the ~~CDI~~ CIV sample was computed using the same subtests that were administered in Ghana. A mean percent correct score was computed across the Number Identification, Addition, and Missing Number subtests from the EGMA.

Literacy Skills

Literacy skills in French were assessed using eight tasks measuring pre-literacy and literacy domains from two sources. Using the Early Grade Reading Assessment (EGRA; RTI International, 2009b), domains included letter-sound identification, nonword decoding, and word reading. Four additional adapted subtasks from EGRA were used and included phonological awareness, phoneme segmentation, synonyms and antonyms (Ball et al., 2022; Jasińska et al., 2022). Finally, one additional measure of phonological awareness from the International Development and Early Learning Assessment (IDELA; Pisani et al., 2018) was also included. The percent correct for each domain was computed, and the score for each domain averaged to create a total score (Cronbach's α = .85).

Executive Function

Two executive functioning domains were assessed: cognitive flexibility was assessed using a tablet-based Hearts and Flowers task (Diamond et al., 2007; α = 0.86). Short-term memory was measured using a visual digit span, where children were shown 13 series of numbers ranging from two to seven digits and asked to write down the numbers they saw in the same order after each series was presented (Finch et al., 2022) (Cronbach's α = .79).

Social-emotional Skills

Socio-emotional skills were measured using IDELA subscale (Pisani et al., 2018) The same subtests that were administered in Ghana were also administered in Côte d'Ivoire (Cronbach's α = .62).

Symbolic and Non-symbolic Numerical Magnitude Processing

The instructions for the Numeracy Screener administered in the Côte d'Ivoire were translated and administered in French (Lafay et al., 2018).

Procedures

[2] We pre-registered that math readiness scores for the ~~CDI~~ CIV sample would be computed using the Numeral Identification, Addition, Subtraction, and Word Problem subtests. However, pilot testing in ~~CDI~~ CIV revealed that the Word Problems subtest from the EGMA was too difficult for children and therefore, it was not administered in our sample. The Missing Number subtest was administered instead and was included in the math composite score.

Data for this study come from the EduqPlus intervention study conducted in 100 schools in the Aboisso and Bouaflé regions of Côte d'Ivoire (Author citation redacted). This school-randomized control trial examined impacts of a text-message based intervention to parents and teachers related to educational engagement and improvement. Fifty public schools within each region (N = 385 in Aboisso, 612 in Bouaflé) were selected by the district education office to participate in the study. Schools were randomly assigned to (i) receive the Eduq+ intervention administered to caregivers and teachers (*n* = 50), or (ii) a control group (*n* = 50).

In each school, the class rosters of CP2 (equivalent to primary 2) were obtained. Thirteen children were randomly chosen from the roster and data collected in the schools in the fall (November 2018; beginning) and spring (June 2019; end) of the school year. At follow-up, data was collected on 2,246 (89.84%) of those children. A random sub-sample, stratified by treatment status, was selected and administered the Numeracy Screener at follow-up. All assessments were administered directly to children in their school. Data collectors were trained for five days and two additional days of field practice.

Results

Descriptive statistics, Pearson correlations, and Bayes Factors of the raw scores across all dependent measures administered in Côte d'Ivoire (~~CDI~~ CIV) are reported in Table 5. We found significant positive associations between the adjusted scores of the Numeracy Screener and school readiness measures of math, socio-emotional, literacy, and executive functioning skills (see Table 5). Bayesian correlation analyses resulted in Bayes factors that are greater than 150 providing very strong evidence for the association between Numeracy Screener scores and school readiness measures (Jeffreys, 1986). One exception was that the association between symbolic comparison and socio-emotional skills failed to reach significance once Bonferroni correction was applied (BF_{10} = .51). These results are consistent with those reported in Ghana further showing that early numeracy skills are related to a broad range of school readiness measures in ~~CDI~~ CIV. Paired samples *t*-test and Bayesian analyses revealed strong evidence to support that children from ~~CDI~~ CIV are more accurate on the symbolic comparison (M = 14.90) relative to non-symbolic comparison task (M = 12.53), $t(341) = 7.14$, $p < .0001$, $d = .39$, 95% CI [1.71, 3.02], BF_{10} = 1.03e+9 (see Figure 1b). Adjusted non-symbolic and symbolic comparison scores significantly correlated with math performance (non-symbolic: $r(340)=.58$, $p < .0001$, and symbolic: $r(340)=.35$, $p < .0001$, see Figure 1c and d respectively). We replicated the finding that the relationship between non-symbolic comparison and math composite scores was significantly stronger than the correlation between symbolic comparison and math composite scores in the ~~CDI~~ CIV sample, $z = 5.75$, $p < .0001$.

Table 5. *Descriptive statistics, Bivariate Correlation Matrix, and Bayes Factors*

Study 2 in Côte d'Ivoire		*Mean*	*SD*	*Skew*	*Kurt*		*1*	*2*	*3*	*4*	*5*	*6*	*7*
1	Numeracy Screener	27.43	11.97	.96	1.26	*r*		.89**	.89**	.53**	.44**	.20**	.40**
						95% CI		.86, .91	.87, .91	.45, .60	.35, .52	.09, .30	.30, .48
						BF10		∞	∞	*4.50e22*	*5.30e14*	*59.46*	*2.32e11*
2	Symbolic	14.88	6.60	1.02	1.23	*r*			.59**	.35**	.27**	.11†	.30**
						95% CI			.51, .65	.26, .44	.17, .37	.01, .22	.20, .39
						BF_{10}			*3.50e29*	*3.55e8*	*3.67e4*	*.61*	*3.11e5*
3	Non-symbolic	12.52	6.85	.76	.70	*r*				.58**	.51**	.24**	.41**
						95% CI				.51, .65	.42, .58	.14, .34	.32, .49
						BF_{10}				*1.43e29*	*5.12e20*	*1229.53*	*1.92e12*
4	Math (EGMA)	.33	.20	.26	-.50	*r*					.68**	.34**	.53**
						95% CI					.61, .73	.24, .43	.45, .60
						BF_{10}					*3.60e43*	*8.42e7*	*5.75e22*
5	Literacy	.19	.16	1.20	1.29	*r*						.46**	.56**
						95% CI						.38, .54	.48, .63
						BF_{10}						*4.54e16*	*2.82e26*
6	Socio-emotional	.64	.28	-.55	-.69	*r*							37**
						95% CI							.27, .45
						BF_{10}							*2.02e9*
7	Executive Function	.49	.14	.35	-.28								

Note. *M* = Mean, *SD* = Standard deviation, Skew = Skewness, Kurt = Kurtosis. Literacy, Socio-emotional and Executive function skills are mean percent correct. $p < .0023$** Bonferroni corrected significance; $p<.01$*; $p<.05^{\dagger}$. BF_{10} = Bayes factor in support of the alternate hypothesis over the null. BF_{10} between 0 – 3 is weak evidence in support of an association. BF_{10} between 3 and 20 is positive support for an association. BF_{10} between 20 and 150 is strong support for an association. $BF_{10} > 150$ is very strong evidence in favor of an association (Jeffreys, 1961).

The Unique Associations between the Numeracy Screener and Math Abilities

We ran a series of hierarchical regression models using the EGMA composite score calculated from the subtests administered in ~~CDI~~ CIV as the dependent measure. We replicated the same pattern of results in Ghana in ~~CDI~~ CIV. Non-symbolic number comparison accounted for significant unique variance in math performance even when controlling for symbolic number comparison, socio-emotional, literacy, and executive function skills (see Table 2). In contrast to prior studies (e.g., Hawes et al., 2019; Nosworthy et al., 2013; Tavakoli, 2016), we found that non-symbolic comparison, but not symbolic comparison, accounted for significant unique variance in math abilities in Ghana and ~~CDI~~ CIV.

Although children in Ghana and ~~CDI~~ CIV showed higher performance on the symbolic comparison task relative to the non-symbolic comparison task, they showed poor performance on the Numeracy Screener relative to first and second grade children from Canada (Nosworthy et al., 2013), and second grade boys from Iran (Tavakoli, 2016). One hypothesis for finding a stronger relationship between non-symbolic comparison and math performance is that a large portion of children in Ghana and CIV do not recognize all numerals from 1-9. However, when children who cannot recognize their numerals are removed from the analyses, the same pattern of results hold such that non-symbolic comparison performance is a significant correlate of math scores when symbolic comparison, executive function, socio-emotional and literacy skills are accounted for in the regression model (see Supplementary Analysis 2; Supplemental Figure 1 and Supplemental Table 2 in the Supporting Information).

We next tested the unique associations between symbolic and non-symbolic comparison and individual subtests from the EGMA administered to children in ~~CDI~~ CIV. We found that although non-symbolic number comparison remained a consistent predictor of performance on the individual subtests from the EGMA, there were some differences in the pattern of results from what was found in the study conducted in Ghana. In contrast to the pattern of results found in Ghana, non-symbolic comparison accounted for significant unique variance in the Missing Number subtest. We additionally found that both symbolic and non-symbolic numerical abilities accounted for significant unique variance in subtraction performance (see Table 6). We pre-registered exploratory secondary analyses that do not inform nor alter the interpretations of our main conclusions. We have included them in the Supporting Information for transparency and in case they are of use to other researchers.

Table 6. *The unique associations between symbolic and non-symbolic comparison and individual subtests from the Early Grade Math Assessment in Côte d'Ivoire.*

Variable	**Numeral Identification**			**Missing Number**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	.17*	.07		-.09	.06	
Male	.07*	.03	.10*	.02	.03	.03
Non-symbolic	.01***	.003	.26***	.008**	.003	.18**
Symbolic	-.002	.003	-.05	-.000	.002	-.000
Socio-emotional	.005	.06	.004	.04	.05	.04
Literacy	.66***	.13	.31***	.89***	.12	.43***
Executive Function	.35*	.14	.14*	.39**	.12	.16**
R^2		.33			.44	
Adjusted R^2		.32			.43	
***F*(df)**		27.39 (6, 335)***			44.66 (6, 335)***	
Variable	**Addition**			**Subtraction**		
	B	***SEβ***	***β***	***B***	***SEβ***	***β***
Intercept	-.06	.04		-.11***	.03	
Male	.03	.02	.08	.03	.01	.10
Non-symbolic	.008***	.002	.31***	.002	.001	.12
Symbolic	.002	.002	.07	.003*	.001	.14*
Socio-emotional	-.02	.03	-.02	.01	.02	.02
Literacy	.36***	.07	.31***	.20***	.05	.25***
Executive Function	.08	.07	.06	.15**	.06	.16**
R^2		.37			.28	
Adjusted R^2		.36			.27	
***F*(df)**		32.44 (6, 335)***			22.13 (6, 335)***	

Note. *p <.05; **p <.01; ***p <.001.

~~Exploratory Pre-registered Secondary Analyses~~

~~To further probe the specificity of the associations between symbolic and non-symbolic magnitude processing and math abilities, we pre-registered testing if the correlations were unique to symbolic math measures by testing whether performance on the Numeracy Screener also correlated with spatial math abilities assessed using the shape identification and sorting subtests from the IDELA~~

(https://osf.io/y32d8?view_only=1f0c09263e9c462b8a589876c2d6f8b7). The symbolic and non-symbolic comparison tasks did not signicantly account for unique variance in spatial math abilities, suggesting that the Numeracy Screener is specifically related to symbolic math assessments (see Supplementary Analysis 2; Supplemental Tables 2 and 3). We also tested whether the strength of the relationship between symbolic and non-symbolic magnitude processing and math scores varied by country. We ran a follow-up multiple regression analysis across both samples additionally including country, as well as interaction terms between country and symbolic and non-symbolic magnitude processing in the model. We did not find a significant interaction between either symbolic comparison or non-sybomlic comparison and country suggesting that the strength of the relationship between non-symbolic comparison and math performance is strong and highly similar across Ghana and CIV samples (see Supplemental Analysis 3 and Supplemental Table 4).

General Discussion

The majority of studies conducted in the Minority World have found that individual differences in symbolic magnitude processing is a stronger predictor of math achievement than non-symbolic magnitude skills. (e.g., Nosworthy et al., 2013; Schneider et al., 2017). Given these findings, researchers have downplayed the role of non-symbolic magnitudes for learning math and have suggested that symbolic magnitude knowledge is a critical foundation for successful math development (e.g., Merkley & Ansari, 2016). However, there is a pressing need for researchers to adopt a global perspective to evaluate whether the foundations for learning math are universal. In the present studies, we examined whether the Numeracy Screener, a paper and pencil assessment of symbolic and non-symbolic magnitude processing, was associated with general math skills in children from Ghana and Côte d'Ivoire (CIV). We specifically tested the hypothesis that symbolic magnitude processing is a stronger correlate of math abilities relative to non-symbolic magnitude processing.

Contrary to our hypothesis, we found that non-symbolic magnitude processing was a stronger correlate of general math abilities than symbolic magnitude processing. Across both West African countries, we found consistent evidence to support a strong moderate association between non-symbolic magnitude processing and general math skills, even when controlling for symbolic magnitude knowledge, executive functioning, socioemotional, and literacy skills. Children from Ghana and CIV were more accurate on the symbolic comparison relative to non-symbolic comparison task demonstrating that the strong association between non-symbolic magnitude processing and math achievement was not driven by higher performance on the non-symbolic comparison task.

Our results diverge from previous studies that have used the Numeracy Screener to assess symbolic and non-symbolic magnitude processing. For example, Nosworthy et al. (2013) found that symbolic comparison performance was a unique correlate of math achievement in first through third grade Canadian children when accounting for non-symbolic magnitude, literacy, and working memory skills. Similarly, Hawes et al., (2019) found that symbolic comparison performance in Kindergarten children accounted for significant unique variance in arithmetic skills and teacher assigned math grades a year later. The symbolic comparison condition of the Numeracy Screener also showed greater sensitivity relative to the non-symbolic comparison condition in distinguishing school-aged children who demonstrated persistent low math difficulties from their typically performing peers (Bugden et al., 2020). The importance of symbolic magnitude knowledge in the development of arithmetic skills was further supported by a study conducted in Iran. Tavakoli et al., (2016) found that performance on the symbolic comparison task accounted for significant unique variance in arithmetic scores in second grade boys. Across studies showing symbolic number comparison to be a stronger correlate of math performance, closer examination of the standardized beta coefficients for the non-symbolic comparison task reveals small non-significant contributions typically ranging from -.095 - .128 (Hawes et al., 2019; Nosworthy et al., 2013; Tavakoli, 2016). In contrast, non-symbolic magnitude skills demonstrated moderate associations with symbolic math skills, with standardized beta coefficients ranging from .13 - .60 across models conducted in Ghana and Côte d'Ivoire. The pattern of results found in West Africa also conflicts with studies that have used computerized paradigms to assess symbolic and non-symbolic magnitude processing. They also diverge from a meta-analysis showing that the association between symbolic magnitude processing and math achievement is stronger than the relationship between non-symbolic magnitude processing and math achievement (Schneider et al., 2016). Taken together, our finding that non-symbolic magnitude processing is a strong moderate predictor of math achievement is inconsistent from the majority of studies conducted in predominantly the Minority World showing that symbolic magnitude processing is a stronger correlate of math achievement.

It is unclear what is driving the conflicting pattern of results found across studies, and therefore, we offer several hypotheses that require further investigation to understand how context influences math development. It remains unresolved whether the approximate magnitude system is involved in learning symbolic representations of number (Sella et al., 2021; vanMarle et al., 2014), or whether it is tangentially related later in development once symbolic representations are learned (Carey & Barner, 2019). One explanation for the diverging patterns of findings across studies is that the approximate magnitude system does play a foundational role for learning math, but that the timing and duration for which it does varies across contexts. For example, our data may suggest that non-symbolic magnitude processing plays a critical role for learning symbolic math in first and second grade children in West Africa. Studies conducted in the Minority World that have failed to find support for this hypothesis could be capturing a developmental window when non-symbolic magnitudes are no longer involved. Evidence to support this idea comes from Fazio and colleagues who found that the relationship between non-symbolic magnitude processing and math performance is stronger in children younger than 6 years old. Moreover, studies have found that non-symbolic magnitude skills support the acquisition of symbolic magnitude knowledge in preschool North American children (Chu et al., 2015; vanMarle et al., 2014). One possibility is that non-symbolic magnitudes support symbolic math development earlier in development, but once children acquire symbolic representations of magnitude, through practice and experience, they begin to form stronger associations among symbols and no longer require accessing non-symbolic magnitudes. Counter evidence to this proposal is that recent findings from the Minority World have found that symbolic magnitude processing at school entry is a stronger predictor of growth in non-symbolic skills than the reverse ~~but non-symbolic magnitude skills do not predict growth in symbolic number knowledge~~ suggesting that acquiring symbolic magnitude skills directly influences non-symbolic magnitude representations (while the converse is not true) (e.g., Kolkman et al., 2013; Lau et al., 2021; Lyons et al., 2018; Matejko & Ansari, 2016). However, because children tested ~~important to note that children in these studies~~ have acquired some symbolic number knowledge, a microgenetic approach starting prior to children learning the meaning of number symbols is needed to fully understand when and how non-symbolic magnitudes support symbolic number acquisition. In other words, our data might support the hypothesis that non-symbolic magnitude processing plays a small role early in development and then as children acquire symbolic number and math knowledge in school, the non-symbolic system plays a less critical role. If this were the case then one might speculate that in countries where children have less experience using symbolic numbers, they rely on non-symbolic magnitudes to carry out symbolic math across a wider developmental window. Follow up studies are necessary to test whether symbolic magnitude processing becomes a stronger predictor of math performance in older children from Ghana and CIV later in development.

A second interpretation although not mutually exclusive from the first is that there are environmental factors operating at both proximal and distal levels to the child that directly or indirectly influence how children think and learn about numbers (Whitehead et al., 2024). For example, proximal factors, such as socioeconomic status and parental education, are associated with math achievement (LeFevre et al., 2009). Specifically, research conducted in Minority World countries has shown that the home learning environment prior to starting formal school is associated with future math skills, suggesting that exposure to enriched learning environment sets children up for success when they start school (Muñez et al., 2021). Cross-cultural evidence also suggests that variability in the home learning environment extends past the Minority World. For example, Susperreguy et al. (2022) found differences in the types of activities that parents engaged in with their children between Chile, Mexico and Canada. A recent study conducted in rural communities in Côte d'Ivoire found that the home environment predicted executive functions which supports the development of numeracy and literacy skills (Jasińska, et al., 2022). These findings suggest that children's experiences with number outside of school shapes how they learn about math in school. Ghanaian culture features a lot of non-symbolic representations in terms of how food products are sold. In particular, Ghana is among one of the countries in West Africa where selling by weight and standard measures is uncommon. For example, tomatoes are grouped in different quantities in bowls and baskets, leaving the buyer to estimate which grouping has more tomatoes. This practice is very common and extends to children's daily lives, particularly those who support their family work. CIV is the largest producer of cocoa in the world. However, in cocoa producing communities, there are high levels of poverty with many families surviving on $1-2 a day (Institut National de la Statistique du Ivory Coast, 2015). Many children assist their family by working in Cocoa production and therefore are spending less time in the classroom (or drop-out all together). Numeracy exposure at home, school enrollment, and attendance rates all of which affect children's math learning trajectories.

There are also distal factors, such as school quality and curriculum, that can affect how and when symbolic and non-symbolic numerical processing relate to overall math ability. We found that mean scores across both conditions of the Numeracy Screener were lower for children in CIV and Ghana relative to children from Canada and Iran. Although there have been several initiatives to improve early education in Ghana, it has been documented that children in both countries are not always attending school and therefore may receive less math instruction. Studies have also shown that children in Ghana begin learning about numbers when they start formal schooling and reports have found that children spend an average of 3.9 hours of math instruction a week (USAID, 2018). It is also the case that instructional practices are described as teacher-centered and children are viewed as passive learners. Observational studies have shown that children are taught by rote learning, copying and imitation, as well as chorus responses, and therefore, focusing on rote rehearsal (Agbenyega, 2018; Akyeampong, 2017). For example, students in the classroom will often recite the count sequence and memorize visually presented numerals. The curriculum remains prescriptive and does not allow teachers to flexibly adapt the curriculum to meet individual students' learning needs. Without opportunities to flexibly engage with symbolic number representations, children in Ghana and Côte d'Ivoire may develop surface-level understanding of symbolic numerals. ~~magnitudes~~. ~~In other words~~, For example, they know that 4 is larger than 2, and 5 is smaller than 9, knowledge that likely reflects rote learning and supports performance on symbolic comparison tasks. However, they may not be drawing on the semantic meaning of numbers to complete these tasks, nor have they had sufficient opportunities to use numbers flexibly in ways that would foster stronger and more precise representations.

In addition to non-symbolic magnitude processing, we also found that literacy and executive function skills were significant correlates of math skills in children from Ghana and CIV. Our finding showing that non-symbolic comparison remains a significant correlate of math performance when accounting for executive function skills, including inhibitory control, is consistent with previous research suggesting that non-symbolic comparison tasks capture core quantitative skills (e.g., DeWind et al., 2015; Starr et al., 2017). Across almost all models, the standardized beta coefficients were larger for literacy skills relative to non-symbolic comparison suggesting that literacy skills are an important correlate of math development. Our findings in Ghana and CIV are also consistent with a previous study conducted in CIV (Whitehead et al., 2024), as well as with findings from Minority World contexts (Vanbinst et al., 2020) demonstrating that early precursors of reading are associated with math skills suggesting that reading and math share overlapping cognitive processes (Hübner et al., 2022).

Limitations

It is important to consider several limitations when interpreting results from the present study. First, our assessment of non-symbolic magnitude processing from the Numeracy Screener includes small quantities (e.g., 1- 4) that are within the subitizing range, as well as large quantities (e.g., 5-9) that are thought to be processed using the approximate magnitude system (Feigenson et al., 2004). It is unclear the underlying cognitive mechanisms that are driving our results and future research should include assessments that separate both cognitive systems. Second, we were unable to collect accurate age data for all children in Ghana and Côte d'Ivoire, and therefore, we are unable to account for age in our regression models. Lastly, drawing conclusions based on cross-cultural and cross-study comparisons is challenging because different studies adopt different methodological approaches that may account for diverging results. A strength of our study is that we administered the same measures in both Ghana and Côte d'Ivoire, enabling us to make direct comparisons across two countries. Importantly, while the math assessments used in these studies are widely used in Majority World countries, they differ from those used in previous studies in the Minority World that also used the Numeracy Screener. We administered the EGMA whereas Minority World studies have used measures such as the Math Fluency and Calculation Subtests from the Woodcock Johnson Tests of Achievement (Nosworthy et al., 2013); teacher-assigned math grades (Hawes et al., 2019), as well as experimenter-developed single-digit (Hawes et al., 2019; Tavakoli, 2016) and double-digit addition and subtraction tasks (Tavakoli, 2016). We note that all these studies, including our own, administered a single-digit arithmetic measure. Although the assessments vary slightly, for example, in whether they were timed or untimed, the association between non-symbolic magnitude processing and arithmetic knowledge remains stronger in Ghana and Côte d'Ivoire compared to studies from the Minority World.

Implications and Future Directions

Nonetheless, our findings have important implications for the debate surrounding the relationship between symbolic and non-symbolic magnitude processing and general math competencies across development. Much of the debate has focused on whether non-symbolic magnitude processing supports symbolic math development. Counter arguments have focused on alternate cognitive explanations, such that any relationship found between non-symbolic magnitude processing and math can be explained by domain general cognitive processes (Gilmore et al., 2013; Leibovich et al., 2017; Leibovich & Ansari, 2016). Our findings suggest that contextual variability is an important consideration to understanding the dynamic associations between symbolic and non-symbolic magnitude processing and math development.

Our results may also have important educational implications. Obtaining quality education is key to break the cycle of poverty (UNESCO) and improve economic growth (World Bank, 2001). Efforts to improve early education can protect against poor health outcomes, and lead to higher economic return (Heckman, 2006). A global approach is necessary to understand how to best invest resources in early childhood programs to reduce the achievement gap between disadvantaged children and their more advantaged peers. The associations found between performance on the Numeracy Screener and math abilities suggests that this simple 2-minute paper and pencil assessment of numerical magnitude processing, has potential to be used to monitor students' progress in countries in the Majority World. Early screening is essential to identify students who are struggling to grasp fundamental skills needed to excel in school. Adopting Westernized tools and approaches might not serve all children. Here, we demonstrate that the Numeracy Screener performance strongly predicts math achievement. Trained research assistants collected the data reported in our study, future investigations are needed to evaluate whether teachers in the Majority World also report practical utility of the Numeracy Screener to assess numerical magnitude knowledge in the classroom.

Conclusions

The current study has not only revealed important insights for numerical cognition, but for the field of cognitive science and education more broadly. We present novel results showing that non-symbolic magnitude processing is a strong and unique correlate of math achievement in school children from Ghana and Côte d'Ivoire. These findings conflict with the majority of studies conducted in Minority World countries highlighting the need for researchers to adopt a global approach to understand human cognition and the role that context plays in learning. It is important for researchers to acknowledge that evidence stemming from the Minority World cannot easily be applied and implemented globally, but instead, researchers need to consider the contextual influences.

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Supporting Information

Supplementary Analysis 1: Does the relationship between the Numeracy Screener and Math hold when we account for age in the subset of children for whom age data was available?

Age data was available for 274 children in our Ghana sample. We reran a multiple regression adding age in the model. We found a positive association between age and math performance. Similar to what we found in the full sample, non-symbolic comparison accounted for significant unique variance in math scores when accounting for gender, age, literacy, socio-emotional and executive functioning skills (see Supplemental Table 1).

Supplemental Table 1. *Multiple regression analyses predicting symbolic math abilities in Ghanaian children with age included as a covariate.*

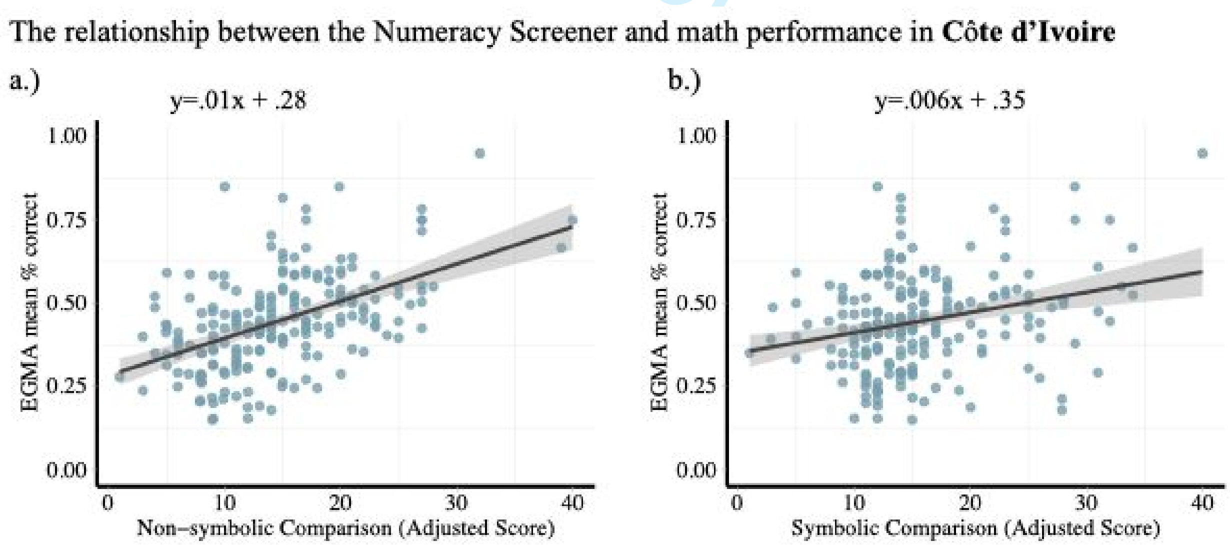
Variable		EGMA	
Model 1	*B*	*SEβ*	*β*
Intercept	-.20**	.06	
Male	-.00	.01	-.002
Age	.01**	.005	.11**
Non-symbolic	.005	.001	.29***
Symbolic	-.00	.001	-.05
Socio-emotional	.03	.05	.03
Literacy	.49***	.04	.52***
Executive Function	.29***	.08	.16***
R^2		.62	
Adjusted R^2		.61	
F(df)		61.27 (7, 265)***	

Note. *p <.05; **p <.01; ***p <.001.

Supplementary Analysis 2: Does the relationship between the Numeracy Screener and Math hold when children who could not recognize single digit numerals are removed the from the sample?

We ran a follow-up analysis to test whether our results were influenced by children's ability to recognize numerals. One possibility is that children from Côte d'Ivoire have poor symbolic math skills relative to children in Ghana and North America and therefore, with less knowledge in recognizing and processing number symbols, it is reasonable that the relationship between non-symbolic skills and symbolic math is strong. In the Côte d'Ivoire data, if children obtained a score below 50% on the number identification task, then they misidentified at least one single digit number. Therefore, children who obtained a score below or equal to 50% were excluded from analyses (*n*=138). There are 204 children from Côte d'Ivoire who could correctly identify single-digit numerals included in the following analyses. Even when excluding children who could not recognize all single digit numerals, our reported pattern of results remained the same.

Paired samples t-test showed that children performed significantly better on the symbolic comparison (M= 15.87) relative to the non-symbolic comparison task (M=14.68), $t(203) = 2.89$, $p = .004$, 95% CI [.38, 2.02], $d = .20$, $BF_{10} = 4.45$. The correlation between non-symbolic comparison and performance on the EGMA, $r(202) = .50$, $p <.001$, 95% CI [.39, .60], BF_{10} = 3.91e11, is significantly stronger than the correlation between symbolic comparison and performance on the EGMA, $r(202) = .28$, $p <.001$, 95% CI [.15, .40], $BF_{10} = 248.65$, (Steiger's test, $t = 3.99$, $p < .001$)(see Supplemental Figure 1). Both correlations decreased when we excluded children who scored less than 50% correct on the Number Identification subtest, but the pattern remains the same, such that the relationship between non-symbolic comparison and math scores are stronger than the correlation between symbolic comparison and math scores.



Supplemental Figure 1. The correlations between non-symbolic and symbolic comparison scores and performance on the EGMA in children from Côte d'Ivoire.

In the sample of children who successfully identified all single digit numerals, we next tested whether non-symbolic comparison performance accounted for significant variance in math scores when accounting for symbolic comparison, socio-emotional, literacy and executive functioning skills. Similar to what we found in the full sample, non-symbolic comparison accounted for significant unique variance in math scores. Symbolic comparison did not significantly account for unique variance in math scores (see Supplemental Table 2).

Supplemental Table 2. *Multiple regression analyses predicting symbolic math abilities in children who could recognize single-digit numerals.*

Variable	**Models predicting EGMA Scores in Ghana**			**Models predicting EGMA Scores in Côte d'Ivoire**		
	B	***Seβ***	***β***	***B***	***SEβ***	***β***
Intercept	-.09	.05		.20***	.04	
Male	.004	.01	.01	.03	.02	.10
Non-symbolic	.004***	.001	.26***	.007***	.002	.30***
Symbolic	-.001	.001	-.03	-.001	.001	-.03
Socio-emotional	.03	.05	.02	-.02	.03	-.04
Literacy	.47***	.04	.50***	.41***	.06	.46***
Executive Function	.32***	.08	.17***	.10	.07	.10
R^2	.56			.46		
Adjusted R^2	.55			.45		
***F*(df)**	69.67 (6, 331)***			28.21 (6, 197)***		

Note. *p <.05; **p <.01; ***p <.001.

We also ran follow up analyses excluding children from Ghana who did not recognize single-digit numerals. In the Number Identification task administered to the sample of children from Ghana, only the first three items were single-digit numerals, the remaining trials were double-digit and triple-digit numerals. There were 10 children who did not identify the first three numbers correctly and were removed from the following analyses. Consistent with results including the full sample, a paired samples t-test revealed that children were significantly more accurate on the symbolic (M = 23.53) relative to the non-symbolic (M = 22.51) comparison task,

$t(339) = 2.85$, $p = .005$, 95% CI [.32, 1.72], $d = .16$, $BF_{10} = 3.26$. Moreover, the correlation between non-symbolic comparison and performance on the EGMA ($r(338) = .52$, $p < .001$, 95% CI [.43, .59], $BF_{10} = 2.17e21$) was significantly stronger than the correlation found between symbolic comparison and performance on the EGMA (r(338) = .34, p < .001, 95% CI [.24, .43], $BF_{10} = 5.25e7$)(Steiger's test for dependent correlations, $t = 5.32$, $p < .001$). Lastly, a multiple regression model revealed that non-symbolic comparison remained a significant unique correlate of performance on the EGMA when accounting for symbolic comparison, socio-emotional, literacy, and executive function skills.

Supplemental Analysis 3: Is there a relationship between the Numeracy Screener and Spatial Math?

Children from the Côte d'Ivoire received additional subtests assessing their shape identification, and sorting abilities based on color and shape. Our pre-registration plan included testing whether symbolic and non-symbolic comparison accounted for significant unique variance in spatial math abilities. A spatial math composite was the mean percent correct across Shape and Color discrimination and Identification subtests from the IDELA. We found that literacy was the only significant predictor of spatial math scores. The symbolic and non-symbolic comparison tasks failed to reach significance (see Supplemental Table 3). These results suggest that the Numeracy Screener is specifically related to symbolic math assessments.

Supplemental Table 3. *Multiple regression analysis predicting spatial math scores.*

Variable	Spatial Math		
Model 1	*B*	*SEβ*	*β*
Intercept	.13*	.06	
Male	.05	.03	.09
Non-symbolic	.004	.003	.11
Symbolic	.001	.003	.02
Socio-emotional	.07	.05	.07
Literacy	.45***	.12	.25***
Executive Function	.23	.12	.11

R^2	.21
Adjusted R^2	.19
F(df)	14.65 (6, 335)***

Note. *p <.05; **p <.01; ***p <.001

However, as outlined in our pre-registration plan, we conducted a confirmatory factor analysis to test whether the data supports our justification to separate and define symbolic math and spatial math constructs. This analysis was carried out using the Lavaan statistical package (Rosseel, 2012) in R using the Maximum likelihood estimation. The latent factors were standardized to allow free estimation of all factor loadings. The model fit was not acceptable with TLI .68 and RMSEA of .19 (90% CI: .16, .22). The individual subtests significantly loaded on each of our defined symbolic and spatial math constructs (see Supplemental Table 4). However, the two-factor model of math abilities did not significantly fit the data better than a single factor construct of math ability χ^2 (1) = 1.23, p = .27 (Chi-square of the difference). In other words, there is no added benefit to separating the individual subtests into symbolic and spatial math constructs using our measures.

Supplemental Table 4. *Factor loadings for the Two Construct Model of Math abilities*

Latent Factor	**Subtest**	**B**	**SE**	**β**	**Z**	**p-value**
Spatial Math	Size & Color Discrimination	.19	.03	.42	6.02	<.001
	Shape ID	.13	.02	.51	6.64	<.001
Symbolic Math	Number ID	.23	.02	.68	12.81	<.001
	Missing Number	.25	.02	.77	14.95	<.001
	Addition	.13	.01	.68	12.93	<.001
	Subtraction	.08	.007	.65	12.13	<.001

Note. *p <.05; **p <.01; ***p <.001; ID = identification.

Supplemental Analysis 4: Does the relationship between the Numeracy Screener and Math Skills vary by country?

To examine whether the strength of the association between symbolic and non-symbolic comparison and math scores is different between countries, we re-ran a multiple regression analysis across both samples. We additionally included country as well as the interaction terms between country and symbolic and non-symbolic comparison scores. Non-symbolic comparison, literacy, and executive function scores accounted for significant unique variance in math achievement scores. We additionally found that country was positively associated with math performance demonstrating that Ghana has significantly higher math achievement scores relative to children in Côte d'Ivoire. There were no significant interactions between either the symbolic comparison or non-symbolic comparison and country. Taken together, the strength of the relationship between non-symbolic comparison and math performance was strong across both Ghana and Côte d'Ivoire samples (see Supplemental Table 5).

Supplemental Table 5. *Multiple regression coefficients testing the interaction between country and performance on the Numeracy Screener in predicting math abilities.*

Variable	Mean Math EGMA		
	B	*SEβ*	*β*
Intercept	.40***	.006	
Male	.02	.009	.04
Non-symbolic	.007***	.001	.33***
Symbolic	-.001	.001	-.04
Country (Ghana)	.18***	.02	.48***
Socio-emotional	.01	.02	.01
Literacy	.52***	.04	.64***
Executive Function	.28***	.05	.22***
Non-symbolic x Country	.002	.002	.06
Symbolic x Country	.003	.002	.06
R^2		.59	
Adjusted R^2		.59	
F(df)		110.30 (9, 680)***	

Note. *p <.05; **p <.01; ***p <.001

Research Highlights

- Non-symbolic magnitude processing is a strong correlate of math abilities in children from Ghana and Côte d'Ivoire.
- The associations remain significant even when controlling for symbolic magnitude processing, literacy, executive functioning, and socio-emotional skills.
- Our results are inconsistent with those found in the Minority World, suggesting that ~~early experiences shape the early precursors~~ there is contextual variation in the development of early precursors important for math development.